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Colorado State Univ., Fort Collins

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ROCKY MOUNTAIN ACIDIFICATION STUDY

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The objectives of this report were to determine the sensitivity of watersheds characteristic of the Rocky Mountain Region and the relationship of watershed sensitivity to geology and soils; to evaluate the extent of current acidification and the potential for increasing acidification with increasing deposition of nitrate and sulfate; to evaluate the results of the preceding in terms of impacts on fish populations; and to develop recommendations for assessment of future trends in both changing water chemistry and impacts on fish populations. Areas selected for study included the Rocky Mountain National Park and Yellowstone National Park, exemplifying two different geologic types that are representative of a large portion of the Rocky Mountain region. Rocky Mountain National Park is primarily underlain by granite and Yellowstone National Park by volcanic materials. Sensitivity is primarily determined by bedrock geology and varies inversely with elevation. High-elevation lakes and streams in the central Rocky Mountain region are very sensitive to acidic deposition. With respect to fish populations there is currently no evidence of chronic acidification and thus no apparent impact on fisheries. However, the very low base cation concentration observed in the headwater drainages of Rocky Mountain National Park suggests extreme sensitivity to acidification. Waters in volcanic areas such as Yellowstone National Park are generally of high alkalinity and do not represent potentially sensitive habitats.

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UNITED STATES
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Dear Colleague:

The Eastern Energy and Land Use Team (EELUT) is pleased to provide you this report on the evaluation of the sensitivity and potential effects of acidic deposition in watersheds characteristic of the Rocky Mountain Region. This report is part of the series of technical reports on air pollution and acid rain developed at EELUT. Previous reports are listed on the inside front cover.

Areas within Rocky Mountain National Park and Yellowstone National Park were selected as representative of geologic types in a large portion of that in the total Rocky Mountain Region. In addition to determining the sensitivity of characteristic watersheds, the study also evaluates the extent of current acidification, the impacts on fish populations, and recommendations for assessment of future trends in both changing water chemistry and fishery impacts.

Please feel free to send suggestions or comments on this report to EELUT.

Sincerely,

R. Kent Schreiber

R. Kent Schreiber
Acting Team Leader, EELUT

FWS/OBS-80/40.17
October 1983

Air Pollution and Acid Rain
Report No. 17

ROCKY MOUNTAIN ACIDIFICATION STUDY

by

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2. James N. Galloway
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EXECUTIVE SUMMARY

As a result of the growing concern for the potential effects of acid deposition in western mountain watersheds, this project was undertaken to:

1. Determine the sensitivity of watersheds characteristic of the Rocky Mountain Region and the relationship of watershed sensitivity to geology and soils.
2. Evaluate the extent of current acidification and the potential for increasing acidification with increasing deposition of nitrate and sulfate.
3. Evaluate the results of the above in terms of impacts on fish populations.
4. Develop recommendations for assessment of future trends in both changing water chemistry and impacts on fish populations.

Areas were selected for study which had minimal human impact and for which the maximum amount of data on soils, geology and water chemistry already existed. The Rocky Mountain National Park (RMNP) and Yellowstone National Park (YNP) areas selected exemplified two different geologic types. The geology of these areas is representative of a large portion of that in the total Rocky Mountain region. In addition, data on precipitation chemistry were available from the National Atmospheric Deposition Program (NADP) monitoring studies in the two parks. In Yellowstone National Park up to 30 years of water chemistry data were available, along with information on geology and soils. In Rocky Mountain National Park a lake and stream sampling program was conducted to collect the water chemistry information. Throughout the project the relationship between water quality data and fish responses determined in research studies in Scandinavia and eastern North America were relied upon to assess potential impacts on fish populations.

RESULTS

The two parks represent a contrast in geologic materials; Rocky Mountain National Park being primarily underlain by granite and Yellowstone National Park by volcanic materials, although the geologic material in one watershed in Rocky Mountain National Park (the Upper Colorado River Basin) is of volcanic origin. The examination of the geochemistry of Rocky Mountain National Park has shown that many areas in RMNP are sensitive to acidic deposition and that this sensitivity is primarily determined by bedrock geology. In addition, sensitivity varies inversely with elevation. The analyses show that watersheds underlain by granite and biotite gneiss and schist are equally

sensitive to acidic deposition. The lakes and streams in these watersheds had alkalinities <200 µeq/l. Waters at the higher elevations (>3300 m) were very sensitive (alkalinity < 100 µeq/l). The Upper Colorado River Basin and the Upper Fall River Basin contains tertiary intrusive rocks in their drainage, resulting in low sensitivity (alkalinity >200 µeq/l). Waters in Yellowstone National Park had alkalinities generally above 200 µg/l, with a few < 200 µg/l on rhyolite or basaltic flows.

The analysis of sensitive aquatic systems have been extrapolated to the Central Rocky Mountain Region by delineating areas underlain by granite biotite gneiss and schist and similar gneisses and schists. Areas underlain by these formations are classified as sensitive (alkalinity <200 µeq/l), lakes and streams located at higher elevations (>3300 m) can be classified as very sensitive (alkalinity < 100 µeq/l). Areas underlain by tertiary intrusive rocks were classified as nonsensitive (alkalinity >200 µeq/l).

The Central Rocky Mountain Region is currently receiving precipitation that is somewhat acidic (ave. annual pH ≅ 5.0, NADP 1982). The analysis of the data collected in RMNP shows that little, if any, acidification of lakes or streams has occurred; however, areas that are subject to periodic deposition of pollutants during upslope air movements from population centers such as Denver may be experiencing some acidification.

As stated, high-elevation lakes and streams in the Central Rocky Mountain Region are very sensitive to acidic deposition. Much of the region is underlain by rock with low buffering capacities that is covered by highly permeable soils with low ion-exchange capacities. As in RMNP, high-elevation lakes and streams in this poorly buffered region probably will become acidified if acidic deposition increases to the level currently experienced in the northeastern United States. An evaluation of the potential impact of increased acidic deposition on specific lakes and streams would require a drainage-by-drainage assessment, as local variability in bedrock, hydrologic flow path, and soil development may have an overwhelming influence on sensitivity.

With respect to fish population there is currently no evidence of chronic acidification and thus no apparent impact on fisheries. However, the very low base cation concentration observed in the headwater drainages of Rocky Mountain National Park suggests extreme sensitivity to acidification. Fish populations present in these low calcium waters may be particularly susceptible to osmoregulatory stress from episodic acidification. The few remaining native trout (Salmo clarki) located in the interior regions of the Rocky Mountains persist only in small isolated headwater drainages. The displacement of these rare and endangered genotypes to headwater drainages also makes them most susceptible to potential acidification in these sensitive habitats. Waters in volcanic areas such as Yellowstone National Park are generally of high alkalinity and thus do not represent potentially sensitive habitats.

RECOMMENDATIONS

It is recommended that long-term watershed studies be established at several points in the Rocky Mountain region. Water samples should be analyzed for major inorganic constituents, DOC, aluminum, alkalinity and total acidity. In addition, surveys of water chemistry should be performed in other mountainous areas, not only in the Rocky Mountain region but also in other areas of the western United States. In addition, an effort should be made to determine the rate of dry deposition of neutral salts, i.e., calcium sulfate.

Behavioral responses and immigration tendencies of S. clarki populations exposed to episodes of acidification should be determined experimentally. Potential for aluminum mobilization in the Rocky Mountain watersheds exposed to increased acid deposition should be studied. Studies of winter-spring water chemistry in headwater catchments should also include evaluation of the movement of trout populations in response to chemical change. The potential sensitivity to acidification of watersheds currently occupied by endangered or threatened populations of S. clarki or of watersheds considered as potential candidate sites for reintroduction should be determined and given special consideration.

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Another important contribution to the data collection was made by William Locke of Montana State University, who provided information on soils on RMNP and aided in the selection of sampling sites. We also wish to thank Dave Stevens of RMNP and Wayne Hamilton of YNP, who facilitated our access to the parks and to the available information on soils, geology and water chemistry.

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Lastly, we wish to express our sincere appreciation to Janice Hill of the Natural Resource Ecology Laboratory Publications Section and her staff, Katie Curry, Kay McElwain and Susan Taylor for their efforts "beyond the call of duty" in organizing, typing and editing this report.

INTRODUCTION

Acid precipitation and its subsequent impact on aquatic and terrestrial ecosystems is a matter of extensive research and debate in much of the industrialized world in the northern hemisphere. Northern Europe, United States, Canada, and Japan, have all experienced an increase in the acidity of precipitation and in many of these areas this increase has been associated with deterioration in aquatic and terrestrial ecosystems. The extent of this deterioration and its relationship to acidic precipitation has been the subject of considerable controversy. However, it appears clear at this time that in the Scandanavian countries, and limited areas of northeastern U.S. and eastern Canada, lake and stream acidification as a result of acidic precipitation has been demonstrated beyond reasonable doubt. In addition, in many of these areas there have been documented declines in fish populations associated with the increase in acidity. Effects on terrestrial systems and their association with acidic precipitation are less well established, but there do appear to be declines in forest productivity in areas of Europe and northeastern United States that are correlated with atmospheric deposition. These observations have spurred initiation of extensive research programs to determine the relationship between acidic deposition and declines in the productivity of terrestrial and aquatic systems (National Research Council 1981).

The emphasis of research to date has been in eastern North America, areas of which now receive rainfall with an average pH of 4.1 or below along with elevated levels of sulfate and nitrate (NADP 1980). In addition, areas in which the most significant impacts of acidic deposition have been demonstrated in aquatic systems are underlain by geologic material of low buffering capacity. Such areas are found in eastern Canada and northeastern United States. The combination of limited buffering capacity of soils and parent materials and elevated levels of acid deposition have led to lake and stream acidification, with subsequent effects on the biotic community. The effects on aquatic systems, particularly the decline in fish populations, has been the most significant factor in encouraging governments and industry that we are dealing with a serious problem which requires not only increased levels of research, but also the development of policy to bring about reductions in anthropogenic emissions of sulfur and nitrogen oxides.

While the emphasis in the eastern U.S. and Canada is understandable because of the documented problems, in terms of both levels of acidic deposition and impacts, it has been noted that the same conditions of sensitivity exist in areas of the western United States including the Rocky Mountains, the Sierras, Cascades, and other western ranges. These areas are primarily of granitic bedrock, and the limited data available has shown that the high elevation lakes and streams have sensitivities comparable to those in the eastern United States and Canada. On the other hand, data from the National Atmospheric Deposition Program (NADP) and other research has not demonstrated that these areas are receiving precipitation with acidity comparable to that of eastern North America. Preliminary data from NADP would indicate that the pH of rainfall in the Rocky Mountain West is averaging 4.8 to 5.0, with a possibility that in some areas at higher elevations the pH may be somewhat below these values. Precipitation with pH values below 5 would generally be considered to be more acidic than normal. This raises the question whether the most sensitive lakes and streams at the higher elevations are being acidified. Because of the importance of these lakes as trout fisheries and their aesthetic value to millions of visitors, it is important to gain a better understanding of the current status of these lakes with respect to buffering capacity and to assess the potential for acidification and subsequent impact on fish populations. A survey of the literature indicates however, that little water chemistry data are available for high lakes (>2500 m) in the central Rocky Mountains.

The most extensive watershed study in this region has been at the Como Creek watershed in the northern front range of the Colorado Rockies (Lewis and Grant 1979). At least 150 weeks of consecutive stream and precipitation chemistry data are available (Lewis and Grant 1979; Lewis 1982), and the first report of acidic deposition in the Rockies was made at this site (Lewis and Grant 1980). The alkalinity in the waters of Como Creek averaged 192 µeq/l as determined by potentiometric titration to pH 4 (Lewis and Grant 1979). Other studies of high mountain lakes include those by Dodson (1981) in the Elk

Mountains of westcentral Colorado. This area, located on the west slope of the Continental Divide, is underlain by quartzite, siltstone, sandstone, and shale (Harte et al. 1983). Dodson (1982) found these lakes to have low alkalinity, 8 to 350 µeq/l. A recent study by Harte et al. (submitted) in the same area reveals alkalinities ranging from 8 to 250 µeq/l with pH values of 5.9 to 7.88. Turk and Adams (1983) have carried out a study of the chemistry of high-elevation lakes in the Flat Tops Wilderness area of western Colorado. The bedrock in this area is predominantly basalt with some granitic outcrops. Alkalinities in this region range from 70 to 1400 µeq/l. In addition, data from a lake survey of the Mount Zirkle Wilderness area by Turk (unpublished) shows alkalinities ranging from 12 to 315 µeq/l. The bedrock in this area is primarily granite. In his study of the South St. Vrain Watershed in the Front Range of Colorado, Thurmon (in press) found that alkalinities in the headwaters averaged 82 µeq/l. This area is underlain by silverplume granite and biotite, gneiss, and schist.

These studies of water chemistry of headwater lakes and streams in the Central Rocky Mountain Region have only recently been conducted. The lack of historical data prevents the evaluation of any long-term trend in acidity. Lewis and Grant (1979) reported an increase in stream hydrogen ion concentrations in the Como Creek watershed over a 150 week period. This record, however, is too short to be considered evidence of increasing acidification. Lewis (1982) reported an average decrease in alkalinity of 180 µeq/l for 104 lower elevation lakes and streams surveyed by Pennak in 1938-1942, and resurveyed by Lewis in 1979. Although Lewis attributed this loss to acidic deposition, the concurrent increase in total dissolved solids (TDS) suggests that hydrologic variability is responsible for this decrease in alkalinity. In addition, a 180 µeq/l loss of alkalinity is much greater than any alkalinity loss observed in strongly acidified lakes in the northeastern United States (Hendrey et al. 1980). Thus, no convincing evidence of acidification in the Central Rockies has yet been presented, although several areas have been shown to be potentially sensitive (alkalinities less than 200 µeq/l) to acidic deposition. Also, none of the studies in the Rocky Mountain Region to date have associated the current alkalinity and pH of high-elevation lakes and streams with potential changes in the future and subsequent effects on fish populations.

In general, the objective of this project was to provide an assessment of lake and stream sensitivity of selected areas in the Rocky Mountain region and to relate this to potential effects on fish populations. It was also felt that by coupling water chemistry data with data on the geology and soils in the sampled watersheds, that a relationship could be established between water chemistry and geology and soils types and that this relationship could be extrapolated to other areas of the Rocky Mountain Region. More specifically the objectives were to:

1. Determine the sensitivity of watersheds characteristic of the Rocky Mountain region and the relationship of watershed sensitivity to geology and soils.
2. Evaluate the extent of current acidification and the potential for increasing acidification with increasing deposition levels of nitrate and sulfate.
3. Evaluate the results of the above in terms of effects on fish populations.
4. Develop recommendations for assessment of future trends in both changing water chemistry and effects on fish populations.

The plan called for selecting areas for the study which had minimal human impact and for which the maximum amount of data on soils, geology, and water chemistry might already exist. The plan relied heavily on the established relationship between water quality data and fish responses as determined in research studies in Scandinavia and eastern North America. After considering potential study sites available, two areas of different geologic type were selected: Yellowstone National Park and Rocky Mountain National Park. The geology of these areas is representative of a large portion of that in the total Rocky Mountain Region. Another factor considered was that each of these parks participated in the National Atmospheric Deposition Program (NADP) precipitation chemistry monitoring network, and therefore had available the necessary precipitation chemistry data to be used in the analysis of the extent of acidification of the surface waters. The existence of information on geology and soils in both parks, while incomplete, proved of considerable value. In Yellowstone National Park, water chemistry data was available for up to thirty years in some lakes. A single season of lake and stream sampling was conducted in Rocky Mountain National Park to determine water chemistry.

The first sections of the report begins with an evaluation of the sensitivity of lakes and streams in Rocky Mountain National Park and Yellowstone National Park. Sensitivity (alkalinity) is related to both soil and bedrock influences, as well as elevational gradients. The following section discusses the relationship of the water chemistry data to fish populations based on currently available fisheries data. Conclusions and recommendations are presented in the final two sections of the report.

ROCKY MOUNTAIN NATIONAL PARK

INTRODUCTION

A discussion of the studies performed in Rocky Mountain National Park (RMNP) is presented in this section of the Rocky Mountain Acidification Study (RMAS) report. Rocky Mountain National Park is located in northcentral Colorado along the Continental Divide. It has an area of 106,700 ha and ranges in elevation from 2,329 m to 4,345 m. Approximately one-third of the area and the 107 named mountains are over 3,353 m high. The mountain building was accomplished by a regional uplift of Precambrian igneous and metamorphic rocks during Late Mesozoic and Early Cenozoic time (Richmond 1974). Volcanic activity has more recently altered the western side of the park. Alpine glaciation during the Pleistocene formed characteristic U-shaped valleys, steep-sided cliffs, and lateral moraines Cirque lakes are common. These geologic characteristics made this park an ideal site in which to evaluate lake and stream sensitivity.

DESCRIPTION OF STUDY WATERSHEDS

Four watersheds were selected within the park boundaries in which to conduct the studies. The geologic criteria used in selecting watersheds were geologic control (bedrock and glacial erosion/deposition) as determined from existing information, with attention being given to the representativeness of selected watersheds to the Rocky Mountain region in general and RMNP in particular. Climatic factors suggested the selection of watersheds on both the east and west side of the Continental Divide. Access to these watersheds by foot trail was also a consideration.

The specific watersheds selected for study were Fall River Basin, Glacier Gorge Basin, East Inlet Basin and Upper Colorado River Basin (Figure 1). Information on the bedrock geologic control of these watersheds is available with the bulk of the data compiled on a 1:48000 scale map (unpublished) by W.

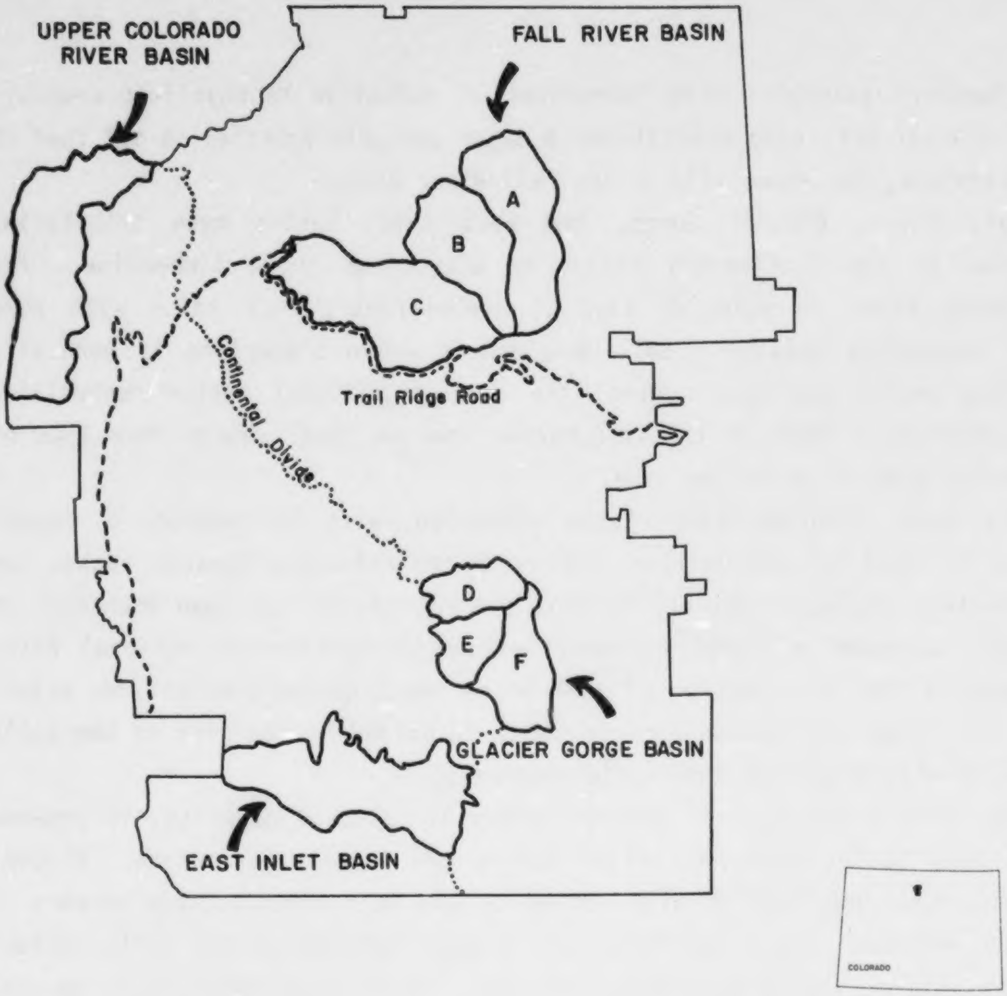
UPPER COLORADO RIVER BASIN
FALL RIVER BASIN
A
B
C
Trail Ridge Road
Continental Divide
D
E
F
GLACIER GORGE BASIN
EAST INLET BASIN
COLORADO

Figure 1. Location of study areas, Rocky Mountain National Park, Colorado. Subbasins are (A) Roaring River, (B) Ypsilon Creek, (C) Upper Fall River, (D) Tyndall Gorge, (E) Loch Vale, (F) Glacier Creek.

A. Braddock, University of Colorado, Boulder. There are also two pertinent, unpublished theses (Abbott 1974; Shroba 1977).

The geology in RMNP is similar to about 70% of the mountainous areas within the Rocky Mountain region. The most extensive geologic material present in the Colorado Rocky Mountain region is Precambrian granites and metamorphic rocks. These rock types are present in three of the four basins selected for this study: Fall River, Glacier Gorge, and East Inlet Basins. The fourth watershed, the Upper Colorado River Basin has as its major rock types Tertiary volcanics with intrusives of andesitic to rhyolitic composition. Glacial till also constitutes a major geologic material in all four of the watersheds, but especially in the Fall River Basin.

Fall River, Glacier Gorge, and East Inlet Basins have tributaries beginning at the Continental Divide at elevations above timberline. The tributaries start in material that is predominantly rock talus with some tundra vegetation present. Soil development above timberline is generally weak thus making geologic control the most significant factor controlling water chemistry. Most of the tributaries have as their source some type of snow field, glacier or cirque lake.

The Upper Colorado River Basin watershed, with its bedrock of intermediate to rhyolitic composition, intrusive and extrusive igneous rocks, has approximately analagous geology to that present in the San Juan mountains of southwest Colorado and the northwest section of Yellowstone National Park. This area is the only section of RMNP where these geologic conditions exist. These rock types contribute more in terms of buffering capacity to the soils because of mineralogy and more rapid weathering.

The third broad type of geologic material, glacial deposits, is present in all four basins with Fall River having the largest percentage. Glacial deposits range from late moraines of up to 200 feet thick to thin veneers in upstream regions. These deposits have a major bearing on the soils encountered as well as the general water quality. The morainal material in general is coarse grained with abundant boulders, gravels and sands. This material is well drained and thus water interacts not only with the soils developed on the glacial deposits but also with the deposits themselves.

Another factor, climatic regimes, has profound influences on watershed characteristics. It is noted that two watersheds, Fall River and Glacier Gorge basins, are located on the east side of the continental divide, while the other two watersheds, East Inlet and Upper Colorado River Basins are on the west side of the divide. This provides a contrast in precipitation levels and vegetation types, both major factors in soil development.

A bedrock and surficial geology map using a U.S. Geological Survey 7.5 minute quadrant topographic map was prepared for each watershed using primarily existing data (Braddock, unpublished; Cole 1977; Abbott 1974). Also, a map using the same base has been prepared showing the geomorphic provinces in each watershed. The map of the geomorphic provinces (talus slopes, scoured bedrock, moraine veneer, etc.), shows the prime source of the soils (parent material) that have developed in those provinces along with the primary vegetation present (Locke, unpublished).

The four watersheds were subdivided on the basis of tributary drainage as follows (Figure 1):

Glacier Gorge: Tyndall Gorge, Loch Vale, Glacier Creek subbasins

Fall River: Roaring River, Ypsilon Lake, Upper Fall River subbasins

East Inlet: Not subdivided

Upper Colorado River: Box Canyon subbasin

Lithologic Units

Igneous and metamorphic rocks are present in the four watersheds and range in age from Precambrian to Tertiary; the metamorphic rocks are confined to the Precambrian. Unconsolidated materials of Quaternary age are abundant in all basins. The major bedrock units exposed in the four watersheds are (Abbott 1974; Cole 1977; O'Neill 1981):

Xqs: Biotite gneiss and schist

Xam: Amphibolite

Xgg: Quartz diorite gneiss

bc: Boulder Creek granodiorite

Ysp: Silver Plume granite

PEa, PEab, PEap: Andesite flows, breccia flows, prophyry

Ngd: Granodiorite of Mt. Richtofen stock

Ngr: Granite of Mt. Cumulus stock

Nvr: Ash flow tuff

The mineralogical compositions of bedrock geologic units are summarized in Table 1. Using the Goldich (1938) weathering sequence and the modal percentages of the lithologic units, a suggested weathering stability classification is shown. The susceptibility to chemical weathering increases to the right. The classification is essentially based on the relative modal

Table 1. Major bedrock units: Composition and relative susceptibility to chemical weathering.

Minerals (by %)	Lithologic units								
	Ngr	Ysp	bc	Nvr[a]	Ngd	Xgg	Xqs	PEa, PEab, PEap[a]	Xam
	Least weatherable -								Most weatherable
Quartz	35	27	31	High	10	30-65	37	None	7-10
Microcline	60	38	26	High	32	7-40	11	Minor	
Orthoclase							3	Minor	
Plagioclase	4	24	25	Minor	40	10-30	22	High	20-40
Plagioclase type[b]		Olig.	And.		And.		Olig.	And.	Labr.
Biotite	1	7	15	Minor	18	15-35	18	High	7-20
Hornblende									20-60
Magnetite		2							5-30
Cordierite							6		
Accessory		2	2						

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[a] Determination of percentage by optical means was not possible. Rating based on known rock type.

[b] Olig. = Oligoclase, And. = Andesine, Labr. = Labradorite.

percentages of mafic minerals, hornblende and biotite, and plagioclase, as these minerals are more susceptible to chemical weathering (Goldich 1938). Some attention has been given to the physical stability of the rock, i.e., schistosity in the biotite gneiss and schist (Xqs). The location of the ash flow tuff (Nvr) in the classification is questionable because of possible influence of the moderately high temperature of formation and the glassy matrix on weathering.

Of the four basins selected for study (two on each side of the Continental Divide), three are dominated by metamorphic rocks and soils derived from those rocks. The third is in a region of volcanic rocks typical of a significant section of the Rocky Mountain region. The three basins representing metamorphic materials differ in the percentage of glacial deposits in the basin vs. the steep slope areas with either thin or no soil.

SAMPLING SCHEME AND METHODS

Chemistry of Surface Waters

Conceptual basis. The general objectives of the RMAS were to determine the sensitivity of waters in the Rocky Mountain region to acidification by acid precipitation and to determine whether this will have an impact on fish populations. An earlier section of this report outlined the strategy for selecting the sampling sites and described how existing geologic and soils information had been used to select systems and subsystems in the Park that are representative of the Rocky Mountain region. Lakes and streams in nine large watersheds (four basins) were sampled on an elevational gradient. For each subsystem, it was expected there would be an elevational trend in the concentrations of the base cations (calcium, magnesium, sodium, and potassium) because these ions are derived from terrestrial ecosystems by the process of soil or parent material weathering. An elevational gradient in the concentrations of the acid anions (sulfate, chloride, and nitrate) was not expected. This concept is illustrated in Figure 2, a theoretical illustration in which concentration of the sum of base cations (C_B) and the sum of the acid anions (C_A) is plotted as a function of elevation. At the point where they intersect, the system has lost all alkalinity and is about to develop strong acidity. In the lower elevation areas where C_B is larger than C_A, there has to be another anion for charge-balance considerations. In these systems, the anion is bicarbonate, which is equated to alkalinity because of the absence of

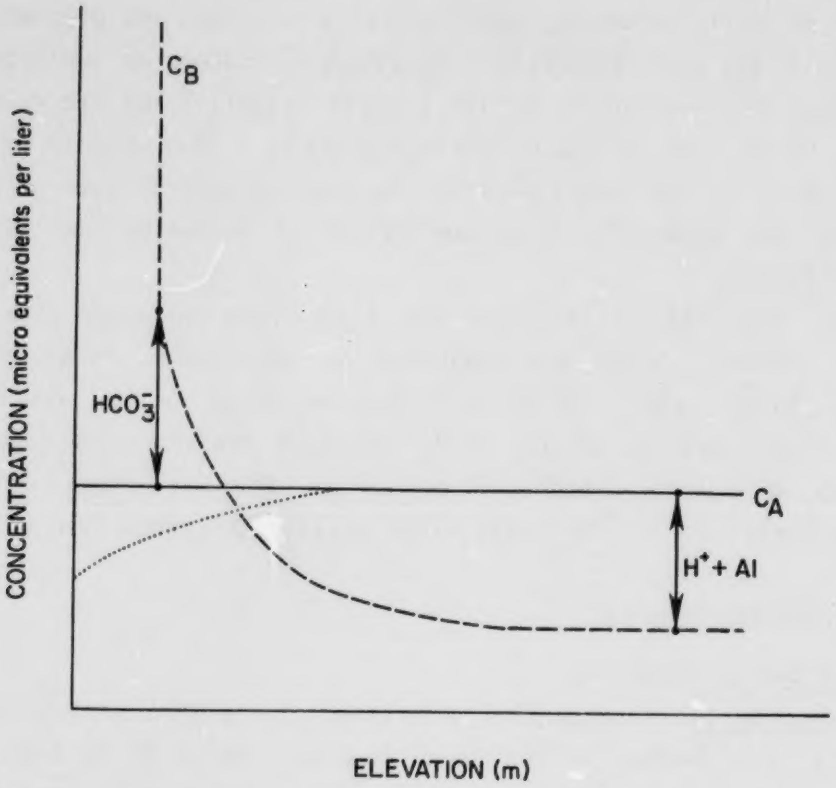


Figure 2. Conceptual behavior of C_B, C_A and alkalinity concentrations as a function of altitude.

Al and organic compounds that could contribute to the alkalinity. For the higher elevations where C_A are larger than C_B, there have to be other cations, again for reasons of charge balance. The cations are hydrogen and aluminum. By definition this region has already developed strong acidity. The effect of increased atmospheric deposition of the acid anions SO_4^{-2}, NO_3^{-1} and Cl^{-1} will cause the horizontal line of C_A to move upward resulting in a larger number of lakes at the lower elevations developing strong acidity. This suggests that the most sensitive (lowest alkalinity) lakes will be at the watershed headwaters.

The dotted line in Figure 2 is worthy of mention. At lower elevations where soil development is more extensive, the process of sulfate adsorption may remove atmospherically derived sulfur from the waters of the watershed. One of the goals of this project was to determine the degree of sulfate adsorption as a function of elevation. Therefore, if the elevational gradient for the acid anions, specifically sulfate, follows the dotted line, we will be able to field test this by the determination of sulfate adsorption capacity.

This concept, relating the concentrations of various species to elevation, was the basis for devising the general water chemistry sampling plan.

Sampling plan. Water chemistry sampling within each sub-basin was carried out in a one to four day period to reduce variation in hydrological conditions. Samples were collected under base flow conditions, i.e., sampling did not occur within 24 hours after rainstorms. Lake samples were collected at each lake inlet, outlet, and center location. Stream samples were taken 25 meters below each confluence and at approximately 150 meter elevation intervals. (Sample location maps are presented in Appendix A.) Stream samples were collected in the middle of the stream under falling water, while lake samples were taken 0.3 meters below the surface at the center of the lake.

Two 250 ml samples were collected at each site in clean polyethylene bottles. Each bottle had been washed with hot water and detergent, rinsed five times with hot tap water and five times with deionized water. The analysis of blank samples indicated no contamination from this cleaning procedure. Each bottle was rinsed three times in situ with sample water before filling. One sample was immediately preserved with reagent grade chloroform for later base cation and acid anion analysis. The sample identification number, location, date, and time of collection were printed on the bottle and recorded in the field log book.

Conductivity and pH were measured in a separate aliquot of sample at the site. Unpreserved 250 ml samples for alkalinity analysis were stored at 5°C for one to two weeks before analysis. The preserved samples were analyzed for chloride, nitrate + nitrite, sulfate, phosphate, silicate, calcium, magnesium, sodium, potassium, and ammonium within two to three months after sample collection. The pH of the stream waters was too high to include aluminum analysis.

Field analyses. Conductivities were measured in the field using a Beckman model RC-16C meter and a Yellow Spring conductivity cell (YSC model 3404). Corrections to 25°C were calculated according to Standard Methods (A.P.H.A. 1976). Field pH measurements were taken with a Corning digital pH meter and a Corning model 476182 pH electrode. The meter was periodically calibrated with cold dilute, strong acids in the laboratory. Each measurement was preceded by a two point calibration using pH 7.00 and pH 4.00 buffer solutions. Corrections for the temperature difference between the sample and buffer were made using meter adjustments. Stream samples for the field pH analysis were collected in polyethylene beakers from the center of the stream. The pH was allowed to stabilize before a reading was taken in a quiecent sample. Lake samples for the field analysis were collected in polyethylene bottles and brought immediately to shore where pH and conductivity measurements were taken. pH was also measured in the laboratory as part of the alkalinity titration.

Laboratory analyses. Calcium, magnesium, sodium, and potassium were analyzed by atomic adsorption spectroscopy using an instrumentation laboratories model 751 AA/AE spectrophotometer. Samples were spiked with a solution of lithium and lanthanum to suppress ionization in the magnesium and calcium analysis (E.M.S.L. 1978). A standard curve consisting of one blank and five standards was prepared between every 34 samples to check for drift. If significant (>10%) drift had occurred, the samples were reanalyzed. The instrument was recalibrated after every standard curve (Emmel 1977).

Sulfate, phosphate, nitrate, chloride, silicate and ammonia were analyzed by automated wet chemistry using a Technicon II Auto-Analyzer. Sulfate was measured using a modification of the Thorin technique developed by the Norwegian Institute for Air Research. Phosphate and silicate were analyzed by standard molybdenum techniques (T.I.S. 1973b; T.I.S. 1976b). Nitrate plus nitrite was measured by the standard cadmium reduction technique (T.I.S. 1972), while ammonia was analyzed using an Indophenol Blue method (T.I.S. 1973a). Chloride was analysed using the standard ferricyanide method modified for low levels (T.I.S. 1976a). In all of the wet chemical analyses, one blank and six standards were run between every 33 samples.

Alkalinities were measured using a potentiometric method developed by Gran (1952). A 50 ml sample was titrated with 0.010 N HCl from pH 4.0 to pH 3.3. The Gran's function of this titration curve was extrapolated to an endpoint to determine the sample alkalinity. A Fisher Accumet 420 pH meter and a Corning model 476182 pH electrode were used for this titration. The meter was calibrated with pH 4.0 and pH 7.0 buffers at the beginning and end of each set of titrations. Both samples and buffers used were at room temperature and air equilibrium. An initial air-equilibrium pH was recorded before each titration.

A summary of the analytical methods is presented in Table 2.

Quality control. The study followed the following protocol on quality control.

1. Precision: To determine precision, 5% of all water-quality samples collected were treated as replicates. The results demonstrated a precision for all measurements of ±10%.

2. Accuracy: In the field, the accuracy of the field pH measurement was assured by calibration of the electrode with standard buffers before each measurement. The pH meter and electrodes were periodically calibrated with cold, dilute acid standards.

Table 2. Analytical techniques.

Measurement parameter	Instrumentation	Technique Summary
Mg	Instrumentation Laboratory Atomic Absorption Spectrophotometer, Model 751	Lathanum added, aspirated in oxidizing flame and read at 285.2 nm using deuterium background correction
Ca	Instrumentation Laboratory Atomic Absorption Spectrophotometer, Model 751	Lathanum added, aspirated in oxidizing flame and read at 422.7 nm
Na	Instrumentation Laboratory Atomic Absorption Spectrophotometer, Model 751	Lithium added, aspirated in reducing flame and read at 589.0 nm
K	Instrumentation Laboratory Atomic Absorption Spectrophotometer, Model 751	Lithium added, aspirated in reducing flame and read at 766.5 nm
SO_4	Scientific Instruments Model A200 with custom-designed manifold	Modification of the thorin technique developed by the Norwegian Inst. for Air Research (NILU)
NO_3	Scientific Instruments Model A200 with stock manifold	Standard Cadmium Reduction technique
NH_4	Scientific Instruments Model A200 with stock manifold	Standard indophenol blue technique
Cl	Scientific Instruments Model A200 with modified manifold	Standard ferricyanide method modified for low levels
SiO_4	Scientific Instruments Model A200 with Auto-Analyzer with stock manifold	Standard molybdenum blue technique
PO_4	Scientific Instruments Model A200 with Auto-Analyzer with stock manifold	Standard molybdenum blue technique
Conductivity	YSI model 3403 Cell, Beckman RC-16C meter	Standard procedure
pH	Corning Model 3 Meter with Corning Model 476182 combination electrode	Standard two-point calibration with pH 7.00 and pH 4.00 buffers
Alkalinity	Radiometer auto burette with Fisher Accumet 420 meter and Corning Model 476182 combination electrode	Air-equilibrated Grans titration

The water-chemistry laboratory at the University of Virginia used two techniques to determine the accurary of analytical measurement. Standard additions were performed on representative samples. In addition, interlaboratory calibration with EPA (1982) and USGS (1981) was conducted by the analysis of blind replicates for all ions. The results of these procedures showed that the accuracy of the analytical measurements was ±10%.

Soils and Surficial Materials

William Locke (unpublished) has produced a general map of major soil (landform-vegetation) groups in Rocky Mountain National Park which was available for our use. Within each basin six to sixteen sites, representative of the major soil groups and providing an altitudinal cross section, were selected for soil sampling (see Appendix A map). With the aid of Locke, soil pits were prepared and a soil-sampling scheme devised.

Soil samples were collected by excavating soil pits by hand to a maximum depth of 50 cm. Samples weighing 300 g to 700 g of each soil horizon exposed were collected and described. These samples were assumed to be representative of the soils encountered in the different landform types in the study area. Representative specimens of rock types were collected and identified. Rock-type names conformed to those used in the Park by Abbott (1974), O'Neill (1981) and Braddock (unpublished).

A complete sample description included colors, texture, structure, rooting depth, and estimates of coarse material. Slope, size of area, and surrounding vegetation was also recorded along with photographs of the sites. Approximately 80-90 samples were collected during the 1981 field season.

Air dried soil samples passed through a 2 mm sieve were used in all laboratory analyses. (The procedures used are described in detail in Appendix B). Briefly, they were as follows: pH was determined in a 1:1 soil water suspension. Exchangeable bases were extracted with 1 N NH_4Ac and determined by Atomic Absorption Spectroscopy. Extractable acidity was determined using a $BaCl_2$-Triethanolamine solution at pH 8.0, followed by a titration. Cation exchange capacity was determined by the sum of exchangeable bases and extractable acidity. Organic matter was estimated by loss on ignition at 500°C and by wet oxidation in $K_2Cr_2O_7$-H_2SO_4 solution (Mebius method). Percent sand, silt, and clay was determined by the pipette method after dispersion in sodium metaphosphate solution.

Selected samples were tested for sulfate absorption by equilibrating 10 grams of soil with 25 ml of dilute K_2SO_4 solution at a pH of approximately 4.1. The solutions were initially at 1, 5, and 10 mg of soil per liter. After shaking with soil and separation by filtration, solutions were analyzed for sulfate loss.

Parent and surficial materials. Determination of the parent materials of the soils was accomplished by geologic reconnaissance of the area adjacent to each soil sample and by binocular microscope examination of the 2- to 4-mm fraction of each soil sample. Glacial till is the parent material for most of the soil samples analyzed and, in turn, is derived from the geologic units upvalley. Therefore, the composition of the 2- to 4-mm fraction of the soil samples is representative of both the glacial till and its parent material, the bedrock units in the area. The areal extent of mapped geologic units, surficial and bedrock, in each basin was determined using a planimetric digitizer and geologic maps. Weathering characteristics of the various bedrock and surficial materials were studied, since they directly affect the type and amount of soil present.

Landform types (Table 3) are helpful in determining the parent material of the soils developed, the thickness of overburden and the existing vegetation. They convey surface features and materials, along with associated vegetation that characterize mappable areas. This information can be obtained

Table 3. Representative landform types (surface features and/or materials) observed in research area.

- Exposed bedrock
- Talus slope
- Unglaciated regolith
- Moraine-ground
  - lateral
  - end
- Moraine veneer
- Wet meadow
- Dry meadow
- Wet tundra
- Dry tundra

by analysis of aerial photographs. Stream gradients for all rivers and streams studied were determined with a linear digitizer.

Seismic refraction surveys were conducted at seven sites to determine the thickness and types of surficial materials overlying bedrock. A Nimbus ES-125 single-channel signal-enhancement seismograph was used. The surveys were made in coniferous forests on moraine veneer, wet meadows and dry meadows. The seismic velocities obtained permitted grouping of geologic materials into four categories: soil, alluvial deposits, glacial till, and bedrock. Numerous factors influenced these values. They include thickness of organic material, water content, clay content, percent of boulders, lithologic makeup of glacial till and type and degree of weathering and/or jointing of bedrock.

RESULTS

Soils and Surficial Materials

Characteristics. The seismic analysis revealed that generally, all soils had velocities corresponding to moist, loamy or silty soils, as reported by Redpath (1973), which indicate a low clay content. The glacial till velocities correspond to values obtained by Redpath (1973) for dry glacial moraine deposits in the Sierra Nevada of California. These deposits had low clay content similar to those encountered in the RMNP project area. Most bedrock velocities were low, indicating a fairly large degree of weathering and/or jointing. This suggests that surface water penetrates to considerable depth.

Seismic profiling revealed the thickness of the soils to be in the range of 0 to 1.9 m; alluvial materials, 3.0 to 3.7 m; and the glacial till, 0 to 7 m (Table 4). The high values represent materials in the center of the stream valleys with decreasing thickness up the sideslopes. Although these depths are not large by comparison with nonalpine surficial materials, they could be quite adequate for buffering of acid precipitation if sufficient clay and organic material existed. Stream gradients are generally indicative of the landform type and are easily obtainable from topographic maps. The steepness of gradient generally is indirectly proportional to the thickness of both glacial and alluvial overburden in the terrain encountered.

The soils tend to be coarse, stony, and shallow with very little evidence of formation of secondary minerals or eluviation. (A detailed description of the soil characteristics of each sampling site may be obtained from the

Table 4. Seismic refraction data summary.

Profile #	Soil	Glacial or alluvial[a]	Bedrock	Landform type
	Velocity (m/s)-thickness (m)	Velocity (m/s)-thickness (m)	Velocity	
1	396-0.7	1699-5.5	2417	Moraine veneer
2	215-1.4	1390-6.2	3135	Dry meadow
3	224-0.8	1117-3.8	2391	Wet meadow
4	374-1.9	None present	3941	Moraine veneer
5	None present	955-3.2	3758	Wet meadow
6	326-1.5	1594-5.3	3208	Moraine veneer
7	318-1.7	None present	2989	Moraine veneer

[a] Unconsolidated parent material underlying soil.

author). Slight development of a color B horizon was detectable in a few of the lower elevation soils developed in glacial till. The major variation in soils within the study area was caused by thickness of deposit, depositional mechanism (local alluvium, till or colluvial deposit) and amount of accumulated organic matter. Differences in mineralogy of the parent material was not evidenced in soil chemical or physical properties. Elevation, especially as it relates to vegetative cover, appears to be important in determining the organic matter content.

Coarse materials (>2 mm dia.) comprised much of the soil volume in most locations. Some of the meadows, however, were essentially stone-free. The talus slopes and most other locations had soils with 10 to 85% coarse fragments in the samples collected. The collection process itself was biased against large fragments therefore the percentages are conservative.

In general the percent base saturation and pH of both the organic layers and mineral soil are low. All pH values are acid, in the range 4.2 to 5.6, with occasional values as low as 3.5 and as high as 6.8. The basic cation status of these soils is generally quite low due to the scarcity of basic rocks in the underlying material. The % base saturation of the soil exchange complex ranges from as low as 2% upwards to 90%, but very few samples exceed 70%. The average for each of the basins ranges from 24 to 48%.

The pH occurring most often in the mineral soil horizons was 5.2 with a strong central tendency around 5.2 In 15 of the 30 locations the mineral soil pH in the top 50 cm was within the range 5.0-5.3 (Figure 3). The surface organic layers had a pH range similar to the mineral soils, but the distribution was shifted slightly toward more acid values.

The clay content of these soils was low. Only two sample locations contained horizons with more than 20% clay (% of <2 mm fraction). It is apparent that most of the exchange capacity is provided by the organic matter. Clay mineralogy was not determined in these samples, but the residual CEC which appears to be due to the clay after subtracting the CEC commonly associated with the organic fraction, indicates a material high in CEC such as vermiculite. Shroba (1977) reported mica alteration and formation of 10-18A mixed layer clays in Alpine soils and more extensive alteration and the presence of vermiculite in the spruce-fir region in the Rocky Mountains.

Sampling of soils was limited to a few locations within each watershed. The variability within watersheds was great and masks many differences that

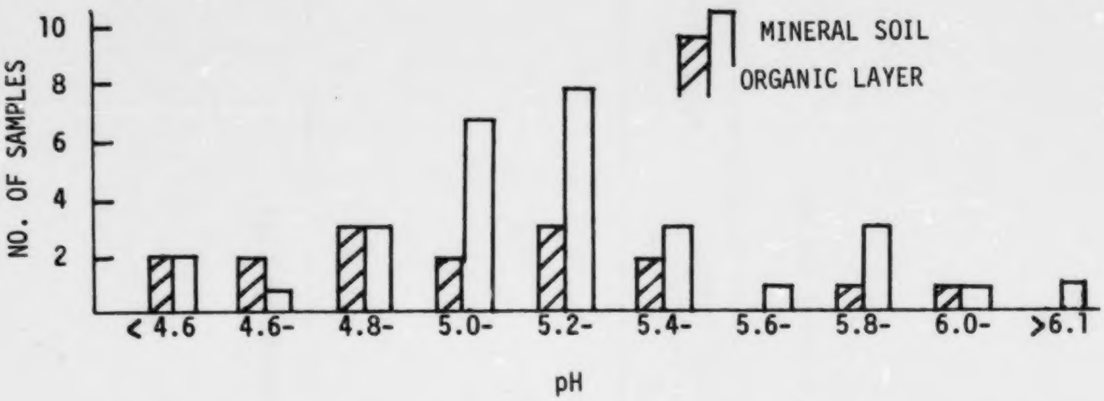


Figure 3. Distribution of pH values in the mineral soil and the surface organic layer of all four watersheds.

may exist between drainage basins (Tables 5 through 8). Fall River basin (Table 7) contained the only soil samples with pH in excess of 6.0. These two mineral soil samples were from the lowest elevations sampled in this study. As a result, the average soil pH in that basin was higher than that in the other three. Otherwise, the average pH in Fall River basin would have been 5.3, essentially the same as those in Upper Colorado and East Inlet basins.

The samples collected in Glacier Gorge Basin (Table 8) are the most acid. Only one mineral soil sample exceeded a pH of 5.2. The mean of all 10 samples in that basin was 5.0, relatively acid for young soils.

The pH of surface organic layers in each basin was usually slightly lower than the mineral soil underneath it. This is a common occurrence in soils with a surface accumulation of organic material under coniferous forests.

A cross section of soil samples were selected for determination of sulfate absorption capacity which can contribute greatly to a system's resistance to the impact of acidic inputs. Sixteen soil samples were tested at 1, 5 and 10 μg S/ml solution for their ability to adsorb sulfate. None of the samples tested removed detectable quantities of sulfate from solution at any of the three concentrations. In many cases the soils released low amounts of sulfate to the solution. This was probably released from the organic matter as a result of the sample drying and rewetting and microbial activity during storage and processing. (Samples for sulfate retention determinations should be stored moist at 0° C until the test is performed.) Based on these

Table 5. Summary of soil properties at four locations in the East Inlet Valley.

Location[b]	Elevation 1000 m	Mineral soil (0-50 cm)					Surface organic		Vegetation type[a]
		Org %	pH	CEC %	BS %	Clay %	Org %	pH	
EI 5	2.90	5	5.5	27	47	22	61	5.0	F
EI 3	3.11	2	5.9	15	69	14	57	6.0	F
EI 2	3.17	8	4.8	34	9	5	48	4.7	M
EI 1	3.35	6	5.1	16	23	8	--	--	G
$\bar{x}$			5.3		37			5.2	

[a] F = coniferous forest, M = wet meadow, G = grass, T = talus slopes with scattered grasses.
[b] For location see designation on maps Appendix A.

Table 6. Summary of soil properties at nine locations in the Upper Colorado drainage.

Location[b]	Elevation 1000 m	Mineral soil (0-50 cm)					Surface organic		Vegetation type[a]
		Org %	pH	CEC %	BS %	Clay %	Org %	pH	
SG-3	3.05	3	4.8	20	12	14	38	4.7	F
D-1	3.14	8	5.6	39	50	--	31	5.4	F
BX-1	3.17	4	5.1	22	21	16	38	5.3	F
HG-2	3.20	2	5.1	20	4	13	52	3.5	F
SG-2	3.23	2	5.2	16	25	13	31	5.2	M
MN-2	3.32	2	4.8	16	22	--	--	--	F
HG-1	3.32	2	5.8	17	45	--	--	--	T
MN-1	3.35	4	5.5	16	33	7	--	--	T
SG-1	3.47	3	5.2	22	44	19	--	--	T
$\bar{x}$			5.2		28			4.8	

[a] F = coniferous forest, M = wet meadow, G = grass, T = talus slopes with scattered grasses.
[b] For location see designation on maps Appendix A.

Table 7. Summary of soil properties at sample locations in the Fall River drainage basin.

Location[b]	Elevation 1000 m	Mineral soil (0-50 cm)					Surface organic		Vegetation type[a]
		Org %	pH	CEC (meq/100 g)	BS %	Clay %	Org %	pH	
L 81-18	2.62	6	6.1	16	56	6	--	--	F
L 80-6	2.65	<1	6.6	3	85	6	--	--	G
L 80-1	2.68	<1	5.3	2	52	4	29	5.9	F
YCS-1	3.08	<1	5.2	6	30	4	--	--	F
81-13	3.20	1	5.3	11	25	7	--	--	F
81-16	3.23	--	--	--	--		60	4.8	M
80-11	3.57	<1	5.5	8	68	4	--	--	T
80-13	3.66	4	5.0	14	23	7	21	4.8	G
$\bar{x}$			5.6		48			5.1	

[a] F = coniferous forest, M = wet meadow, G = grass, T = talus slopes with scattered grasses.

[b] For location see designation on maps Appendix A.

Table 8. Summary of soil properties at sample locations in Glacier Gorge Basin.

Location[b]	Elevation 1000 m	Mineral soil (0-50 cm)					Surface organic		Vegetation type[a]
		Org %	pH	CEC (meq/100 g)	BS %	Clay %	Org %	pH	
GC-4	2.80	1	5.1	8	20	9	65	4.9	F
TG-4	3.08	5	5.0	26	1	19	25	4.6	F
GC-3	3.08	3	4.6	12	2	9	62	4.3	F
TG-3	3.14	1	5.2	17	39	7	--	--	T
AC-3	3.20	5	5.1	20	14	6	65	5.5	M
TG-2	3.35	9	4.3	48	15	10	55	5.2	G
GC-2	3.41	4	5.2	9	39	3	46	5.1	M
GC-1	3.44	2	5.2	4	37	3	--	--	T
AC-1	3.47	13	4.4	32	16	16	--	--	G
TG-1	3.51	7	5.8	19	52	7	--	--	T
$\bar{x}$			5.0	20	24			4.9	

[a] F = coniferous forest, M = wet meadow, G = grass, T = talus slopes with scattered grasses.
[b] For location see designation on maps Appendix A.

tests, it is obvious that these soils have very little if any sulfate absorption capacity at S concentrations up to 10 μg S/ml at a pH of 4.1.

Soil buffering capacity. The soils of the Rocky Mountain National Park at the higher elevation (above 2800 m) are only slightly developed. They have surface organic horizons in some cases and usually have a darkened A horizon underlain by slightly weathered material derived from granites, diorites and other rocks low in bases. The soils are coarse, low in clay, low in basic cations and relatively acid (modal pH 5.2). The organic matter provides most of the cation exchange capacity and there is no evidence of sulfate adsorption capacity.

The physical properties of these soils--coarse, high in sand, low in clay and steeply sloping--promote rapid movement of water to the streams and lakes. Residence times of water will tend to be short especially at the higher altitudes where there is less vegetation, thinner soils and less accumulated organic matter. Much of the water flow will be rapid and through coarse channels such that only a small percentage will approach equilibrium with the soil materials.

The chemical properties, low base saturation, low pH, and low cation exchange capacity provide little opportunity for neutralizing acidic inputs or providing significant alkalinity to the water system. If acidic deposition in the region reached pH values in the low 4.0s there would be a potential for the soil to buffer the pH upward slightly. However, since most water moving through these coarse soils will not have a residence time sufficient for equilibration with the soil, there would be little effect on acidity. The current situation with the soils more acid than the streams indicates that the soils are not controlling the aquatic system pH. Since the dominant soil pH is only slightly above 5 and the exchangeable basic cation supply is low, these soils would not be expected to provide strong buffering of the ecosystem against acidification.

Even though aluminum was not determined in this study the present pH of these soils indicates that aluminum concentrations in the soil solution are not high. A lowering of soil pH to 4.5-4.6 would cause a significant increase in aluminum in soil solution. Some additional aluminum would reach the aquatic system, but much more information would be needed to quantify the expected change in aluminum.

The soil properties already mentioned plus the absence of sulfate absorption capacity indicate that these soils should be considered in a "sensitive" category. They are among the soils which have low capacity to absorb and neutralize acidity and therefore the associated aquatic systems would not be protected from pH change by the soil ecosystem (Galloway et al. 1983). The soil itself is probably resistant to rapid acidification. The abundance of relatively unweathered minerals provides the soil's major buffering against lowering of the pH much below its present values.

Chemistry of Surface Waters

The lakes and streams in RMNP are characterized by low ionic strength. An average concentration for the inorganic constituents are presented in Table 9. The raw data for all of the measured constituents of the more than 150 samples are presented in Appendix C, along with sampling dates for each subbasin. On an equivalent basis, the relative concentrations of the base cations are Ca>>Na>Mg>>K for most of the watersheds, although magnesium concentrations are greater than sodium in the Upper Colorado and Upper Fall River Basins.

The Ypsilon Creek, Tyndall Gorge, Loch Vale, and Glacier Gorge subbasins had similar stream chemistry. These watersheds are characterized as having lower alkalinity and base cation concentrations than the rest of the study area. Roaring River and East Inlet had slightly higher alkalinity, base cation, and silica concentrations. The Upper Fall River Basin had significantly higher concentrations of these constituents, while the Upper Colorado River Basin had the highest alkalinity, base cation, and sulfate concentrations of any of the watersheds.

DISCUSSION

Relationship of Surface Water Chemistry to Atmospheric Deposition, Elevation, Soils, Surficial Materials and Geology

Calculation of "excess" cations. The streams and lakes of RMNP have very low cation and anion concentrations. In the watersheds underlain by granitic and metamorphic rock, the average C_B (Na + K + Mg + Ca), is only ~85 μeq/l (Table 9). In such dilute waters, the atmospherically deposited base cations may comprise a significant fraction of the stream water cation concentration. Previous researchers have corrected surface water chemistry data for the

Table 9. Mean ionic concentrations in Rocky Mountain National Park watersheds.[a]

Watershed	pH	Alk	Na	K	Mg	Ca	NH_4	Cl	NO_3	SO_4	SiO_4	C_A	C_B
Roaring River	6.9	74.4	29.0	3.6	21.7	66.5	0.1	6.0	8.3	34.7	68.8	123.4	121.0
Ypsilon Creek	6.6	48.0	22.9	4.1	15.2	43.6	0.1	3.4	9.8	30.2	61.3	91.4	86.2
Upper Fall River	7.1	180.5	40.2	7.5	67.3	106.9	0.1	7.9	4.9	46.3	110.8	239.6	222.0
Andrews Creek	6.5	38.8	16.1	3.7	13.1	55.7	0.0	3.7	12.5	32.3	36.5	87.3	88.9
Loch Vale	6.0	41.2	15.0	3.1	13.9	52.9	0.4	4.5	17.1	28.2	33.3	91.0	86.2
Glacier Creek	6.6	40.3	14.2	3.0	10.0	46.3	0.1	3.1	11.3	13.3	32.8	68.0	73.8
Upper Colorado River	7.5	331.8	34.6	7.6	80.0	234.3	0.3	7.9	6.3	84.3	81.5	430.3	357.1
East Inlet	6.8	85.5	26.5	2.5	16.0	90.0	0.1	4.2	5.6	35.7	67.9	131.0	125.5

[a] All concentrations are in µeq/1, except SiO_4, which is in µM/1.

atmospherically deposited base cations by substracting the "seasalt" contribution (Henriksen 1980; Almer et al. 1978). Although RMNP does not receive sea salt in its precipitation, the evaporite basins and arid regions upwind of the park result in the wet and dry deposition of base cations in the form of dust and salts (Gosz 1975). In an effort to separate "excess" cations (those released as a result of acid buffering reactions) from atmospherically deposited cations, we have made a correction for atmospheric deposition. Chloride, a conservative element with no terrestrial source (i.e., not present in the bedrock) is used to make this correction. The calculation is made by subtracting from each cation concentration the product of the chloride concentration at that sample site and the ratio of that element to chloride in precipitation (NADP 1982). The result is the precipitation corrected or "excess" concentration--e.g., $Na^* = Na - (Cl \times Na_{precip.})/Cl_{precip.}$ (* indicates "excess" concentration). Some base cations, especially potassium, are taken up by the ecosystem. As a result, our precipitation-corrected concentration of this element may turn out to be negative. If the calculation results in a negative value for an element, the precipitation-corrected concentration is taken as zero. The results of these calculations are presented in Table 10. This method of calculating the "excess" base-cation concentration ($Na^* + K^* + Mg^* + Ca^* = C_B^*$) is a correction for the maximum contribution of C_b ($Na + K + Mg + Ca = C_B$) by wet deposition.

The stochiometry of primary dissolution reactions provides a check on this correction, since the release of base cations by mineral dissolution is accompanied by the concurrent release of H_4SiO_4, e.g.:

$$\underset{\text{(oligoclase)}}{Na_{0.7}Ca_{0.3}Al_{1.3}Si_{2.7}O_8} + 3.45\ H_2O + 1.3\ H_2CO_3 = 0.65\ \underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4}$$

$$+ 1.4\ H_4SiO_4 + 0.7\ Na^{+1} + 0.3\ Ca^{+2} + 1.3\ HCO_3^{-1}$$

$$3\ \underset{\text{(biotite)}}{K_2(Mg_3Fe_3)Al_2Si_6O_{20}(OH)_4} + 24\ H_2O + 18\ H_2CO_3 =$$

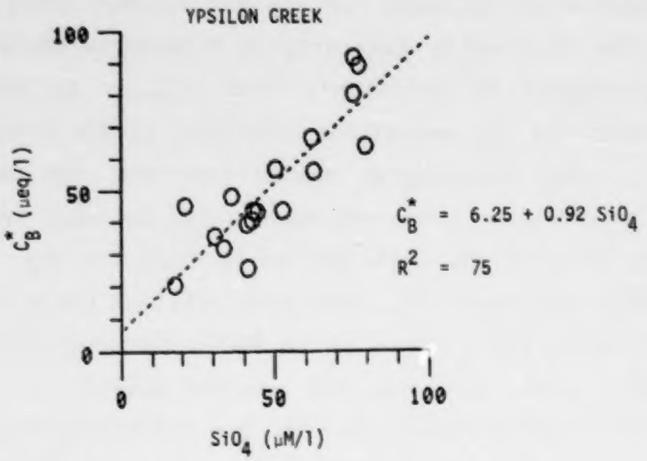
$$2\underset{\text{(vermicullite)}}{(Mg_3Fe_3)Al_3Si_5O_{20}(OH)_4 \cdot 8\ H_2O} + 6\ K^{+1} + 3\ Mg^{+2} + 3\ Fe^{+2} + 8\ H_4SiO_4 + 18\ HCO_3^{-1}.$$

Table 10. Comparison of mean of uncorrected (U) and "excess" (E) base cations.[a]

Watershed	C_B	Na	K	Mg	Ca
Roaring River (U)	121.0	29.0	3.6	21.7	66.5
(E)	72.3	21.9	0.0	11.7	39.3
Ypsilon Creek (U)	86.2	22.9	4.1	15.2	43.6
(E)	56.2	18.8	0.3	9.4	28.2
Upper Fall River (U)	222.0	40.2	7.5	67.3	106.9
(E)	155.2	30.7	0.0	53.8	71.2
Andrews Creek (U)	88.9	16.1	3.7	13.1	55.7
(E)	57.3	11.9	0.0	7.3	38.1
Loch Vale (U)	86.2	15.0	3.1	13.9	52.9
(E)	47.9	9.6	0.3	6.1	32.4
Glacier Creek (U)	73.8	14.2	3.0	10.0	46.3
(E)	47.6	10.5	0.2	4.8	32.5
Upper Colorado River (U)	357.1	45.6	7.7	77.8	218.1
(E)	280.1	35.1	1.4	63.0	181.0
East Inlet (U)	125.5	26.5	2.5	16.0	90.0
(E)	91.5	22.5	0.0	8.8	60.6

[a] All concentrations in μeq/l.

We can assess the accuracy of our estimate of C_B* by comparing the corrected C_B* to silica concentrations (as moles of SiO_4^{-4}). Graphs of C_B* vs. SiO_4^{-4} for Loch Vale and Ypsilon Creek watersheds, with low intercepts show that our correction is appropriate for the watersheds with lowest alkalinity (Figure 4). The variation in the slopes of the regression lines among the watersheds reflects a difference in the distribution of minerals. Watersheds with a slightly greater percentage of biotite will have larger slopes than those with more oligoclase in their drainage according to the different stochiomatry of the weathering reactions. This check on our calculation of C_B* is not



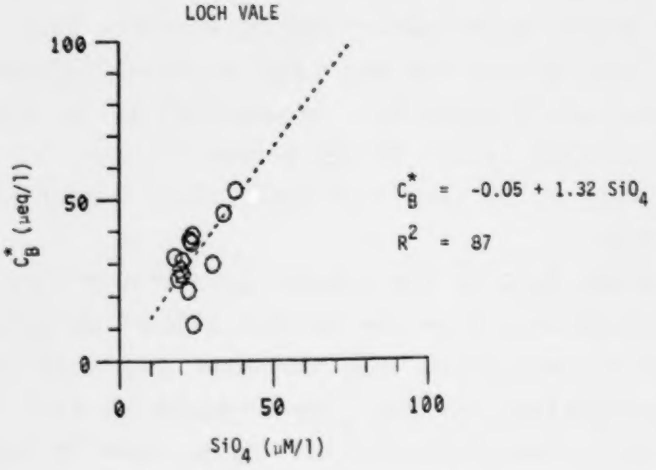


Figure 4. "Excess" base cations vs. silica for two sensitive watersheds in RMNP.

appropriate in watersheds where nonsilicious minerals and soil cation-exchange reactions play a large part in the geochemistry (i.e., the Upper Colorado River and parts of the Fall River basins).

Atmospheric deposition and water chemistry. Researchers have shown that the predominent direction of air mass movement over the Front Range of the Central Rocky Mountains is from west to east (Barry 1973), with periodic upslope movement from the east (Kelley and Stedman 1980). Although most of the precipitation received by this area is dropped by the westerly air masses, the upslope transport of pollutants from sources to the east may have a profound influence on the deposition chemistry of the Front Range (Kelley and Stedman 1980). The atmospheric deposition from the westerly air masses contains little sea salt (Junge and Werby 1958) but does result in the wet and dry deposition of airborne dust and salts from the dry, windy areas to the west (Gosz 1975). As a result, RMNP precipitation has a relatively high base cation concentration [22.0 µeq/l Ca in RMNP, compared with 13.0 µeq/l in the Adirondacks (NADP 1982, Altwicker and Johannes 1980)].

The nitrate concentrations in RMNP are relatively high, comprising 35.6% of the acid anions in precipitation, compared with 28.7% at Hubbard Brook (NADP 1982). These high nitrate concentrations are probably the result of upslope transport of NO_x from the Denver metropolitan area (Kelley and Stedman 1980). The bedrock in RMNP contains only trace amounts of chloride (Lovering and Goddard 1950), while sulfur-bearing minerals (e.g., chalcophyrite and gypsum) are found only in the Upper Fall River and Colorado River basins. As a result, atmospheric deposition is expected to be the primary source of chloride and nitrate in all of the streams in RMNP, as well as the primary source of sulfate in the waters of East Inlet, Glacier Gorge, Ypsilon Creek, and Roaring River.

Stream water chloride and nitrate concentrations are fairly uniform over the park, although East Inlet, on the west side of the continental divide, has lower nitrate concentrations than the other four watersheds (Table 9). Two plausible explanations for the lower nitrate in East Inlet are (1) less deposition from upslope air masses bearing NO_x from the Denver area and/or (2) more biological activity. Chloride and sulfate concentrations show little variability with elevation, indicating negligible variation in the atmospheric contribution of elements with elevation (Figures 5 and 6). Nitrate, the most biologically active anion, shows some variation over elevation, with the highest nitrate concentrations above the timberline, where biological activity is lowest (Figure 7).

Streamwater chemistry and elevation. Elevation is related to several parameters that may effect streamwater chemistry. The thickness of surficial deposits (glacial till, alluvium, loess, and soils) and the length of flow path increase with decreasing elevation as we descend from headwater lakes

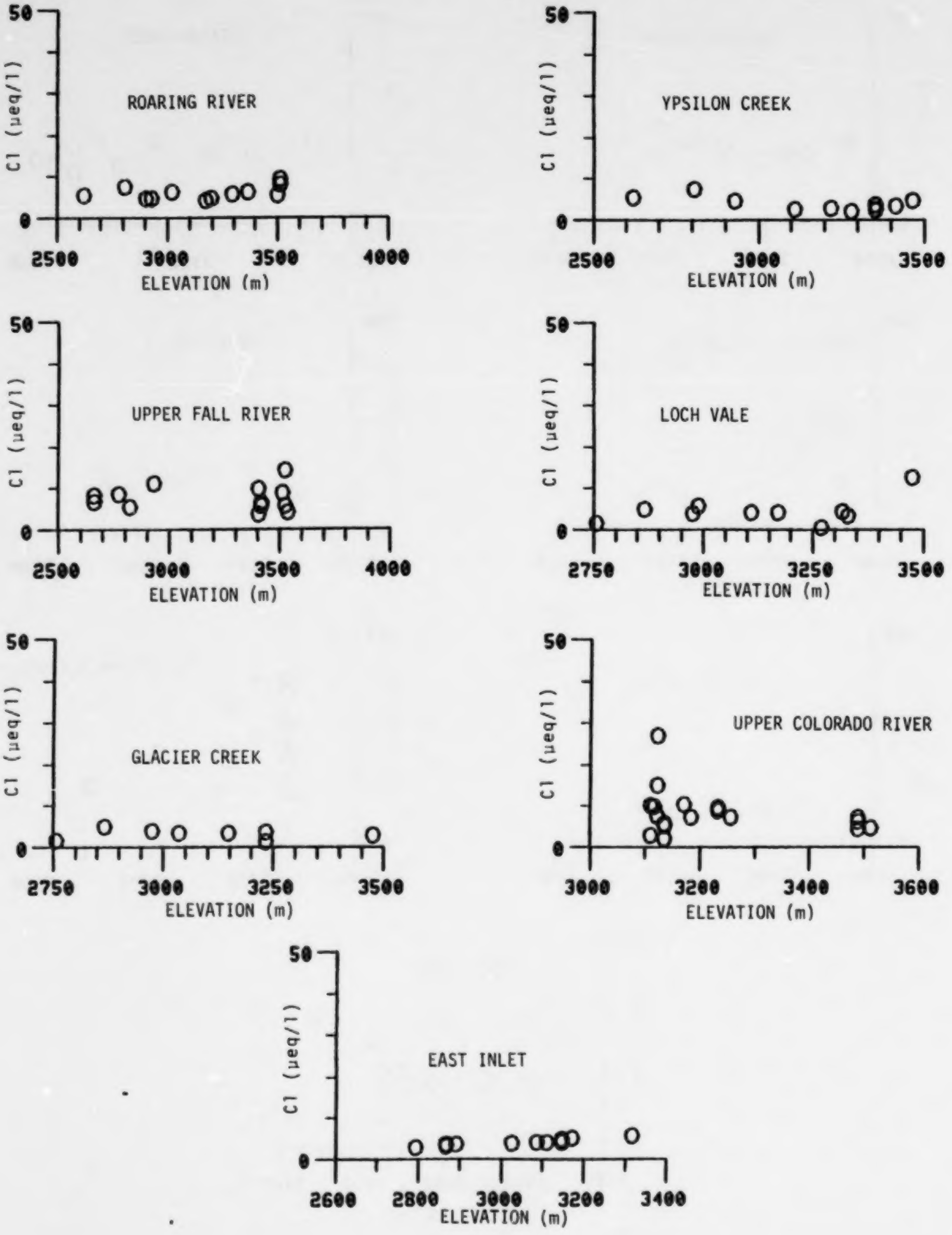


Figure 5. Graphs of Cl vs. elevation for subbasins in RMNP.

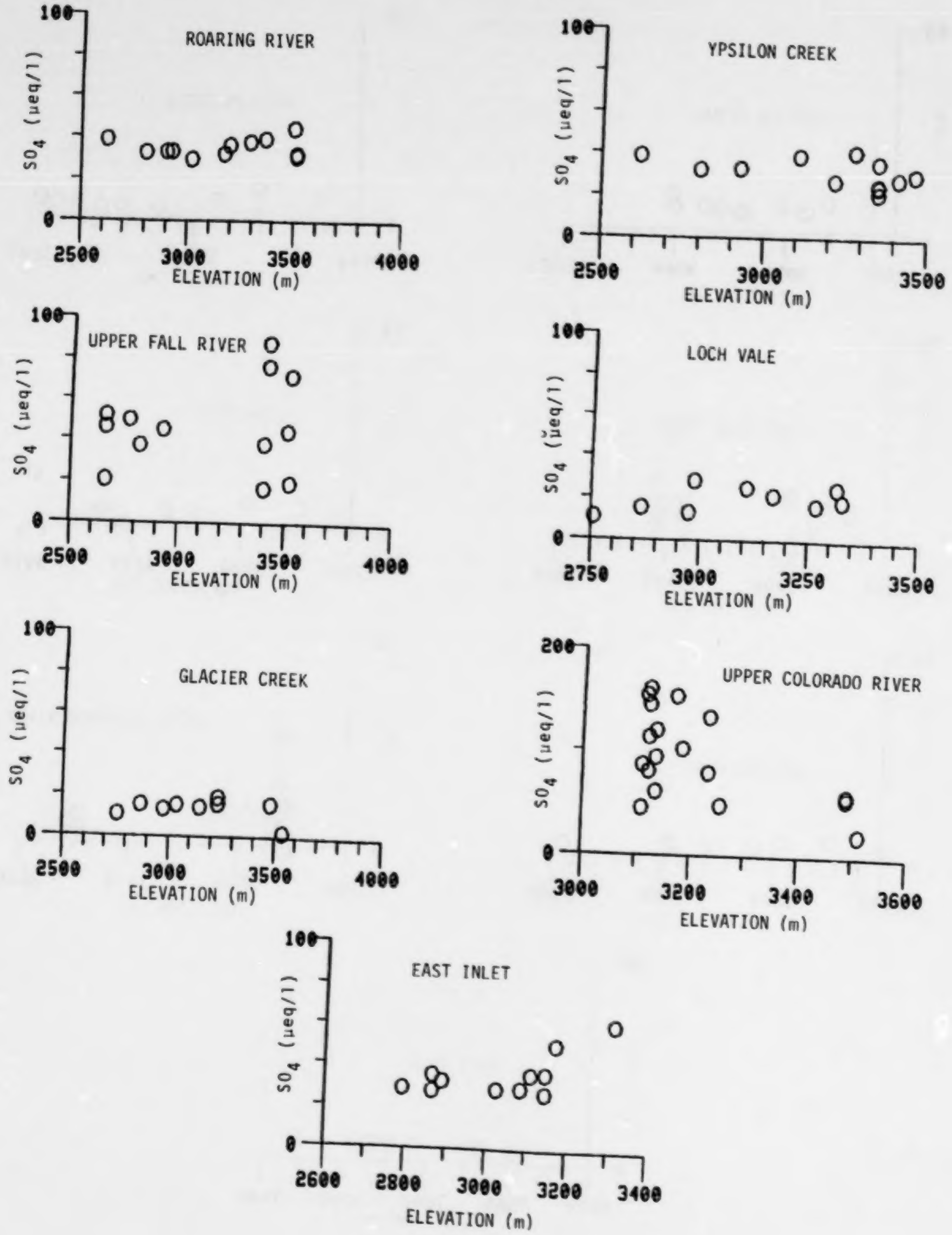


Figure 6. Graphs of SO_4 vs. elevations for subbasins in RMNP.

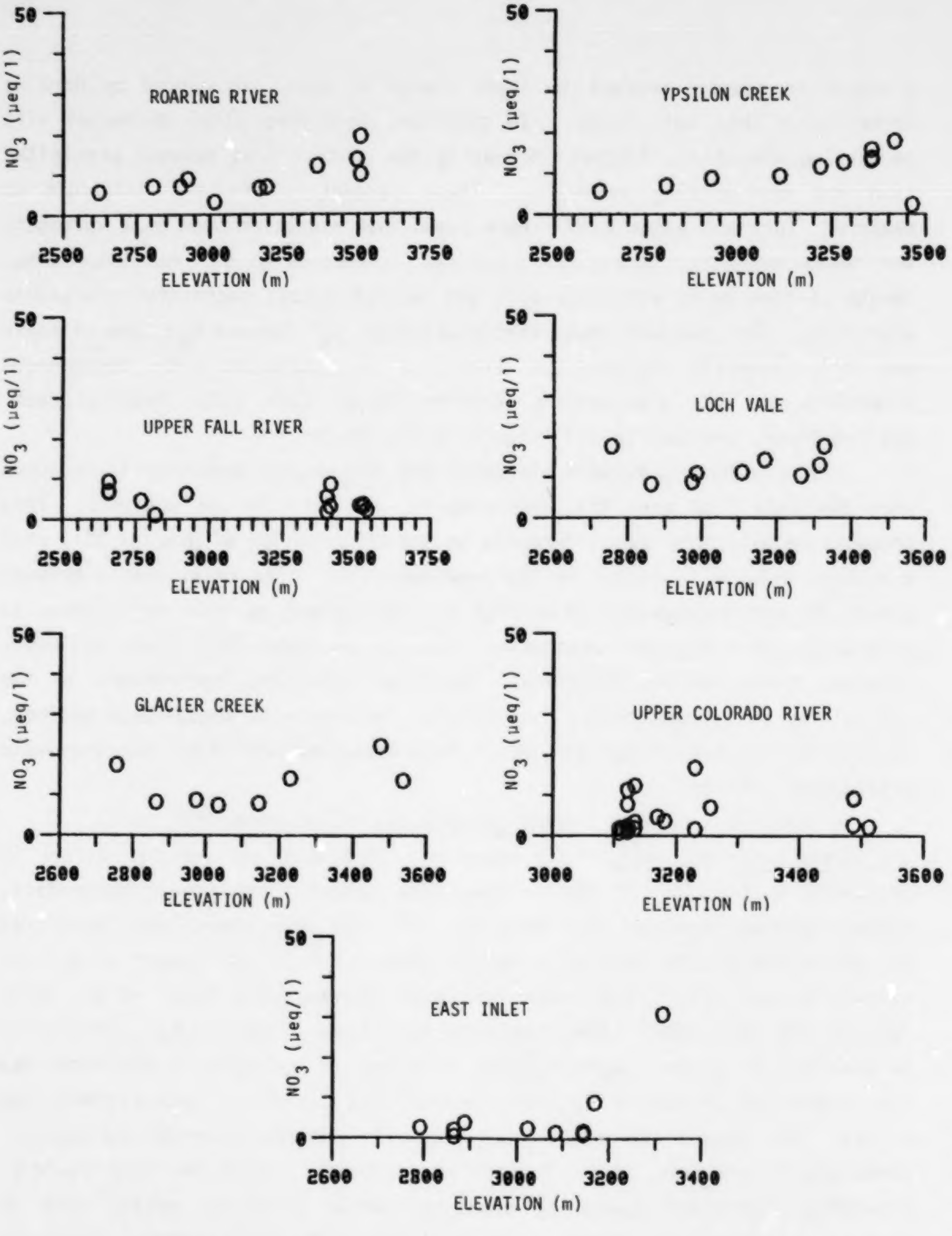


Figure 7. Graphs of NO_3 vs. elevation for subbasins in RMNP.

situated on scoured bedrock to lower elevation lakes surrounded by moraine veneer with thin soil cover. In addition, watershed slope decreases with decreasing elevation, further increasing the contact time between precipitation and neutralizing materials. These parameters are all difficult to measure. Turk and Adams (1983) have shown that elevation used as a surrogate for these and other unmeasured watershed parameters (e.g., residence time, length of flow path, effective soil and bedrock area), successfully predicts alkalinity. Our analysis shows that alkalinity, C_B* (excess C_B), and silicate are all inversely related to elevation in subbasins with homogeneous mineralogy and low alkalinities (Glacier Gorge, Loch Vale, Ypsilon Creek, Roaring River, and East Inlet) (Figures 8 through 10).

This relationship between elevation and streamwater chemistry is obscured when the data from more than one subbasin are used in the analysis. This probably results from the differences in the distribution of glacial till over elevation between subbasins in the same watershed. The relationship between elevation and streamwater chemistry is overwhelmed by the variability in mineralogy and subsequent weathering rates in the Upper Fall River and Upper Colorado River basins (Figure 8). Although elevation contributes to the variability of stream chemical composition in areas with homogeneous bedrock, variability in mineralogy and other interwatershed variables can overwhelm altitudinal effects.

Relationships between bedrock geology, surficial materials, soils and stream water chemistry. The chemical composition of natural waters is primarily a function of the interactions between atmospheric deposition, bedrock geology, and surficial deposits. Previous researchers have found that an area's ability to neutralize acidic deposition is the result of mineral weathering and soil ion-exchange reactions (Norton 1980; McFee et al. 1977; Johnson and Cole 1980). Under pristine conditions, the chemical dissolution of minerals by carbonic acid results in a loss of hydrogen ion (acidity) and the production of alkalinity (acid-neutralizing capacity), base cations, and silica. The rates of these reactions vary with the mineralogy of the bedrock. Carbonaceous minerals, such as calcium carbonate, dissolve very rapidly, providing "infinite" buffering capacity, while silicious rocks, such as granite, dissolve very slowly, offering little buffering capacity. Surficial materials also play an important role in buffering acidic deposition, as soils neutralize acidic deposition through cation and anion exchange.

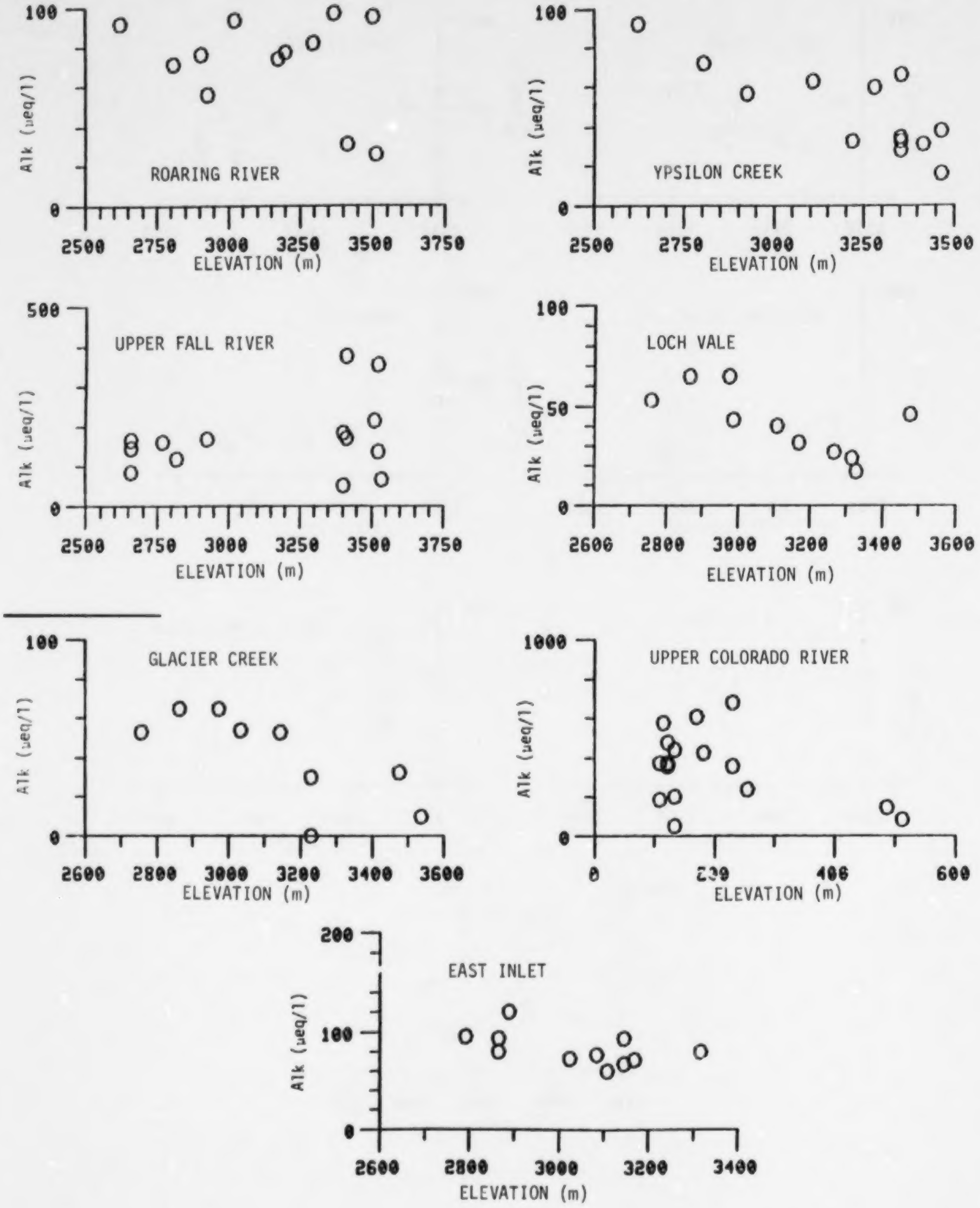


Figure 8. Graphs of alkalinity vs. elevation for subbasins in RMNP.

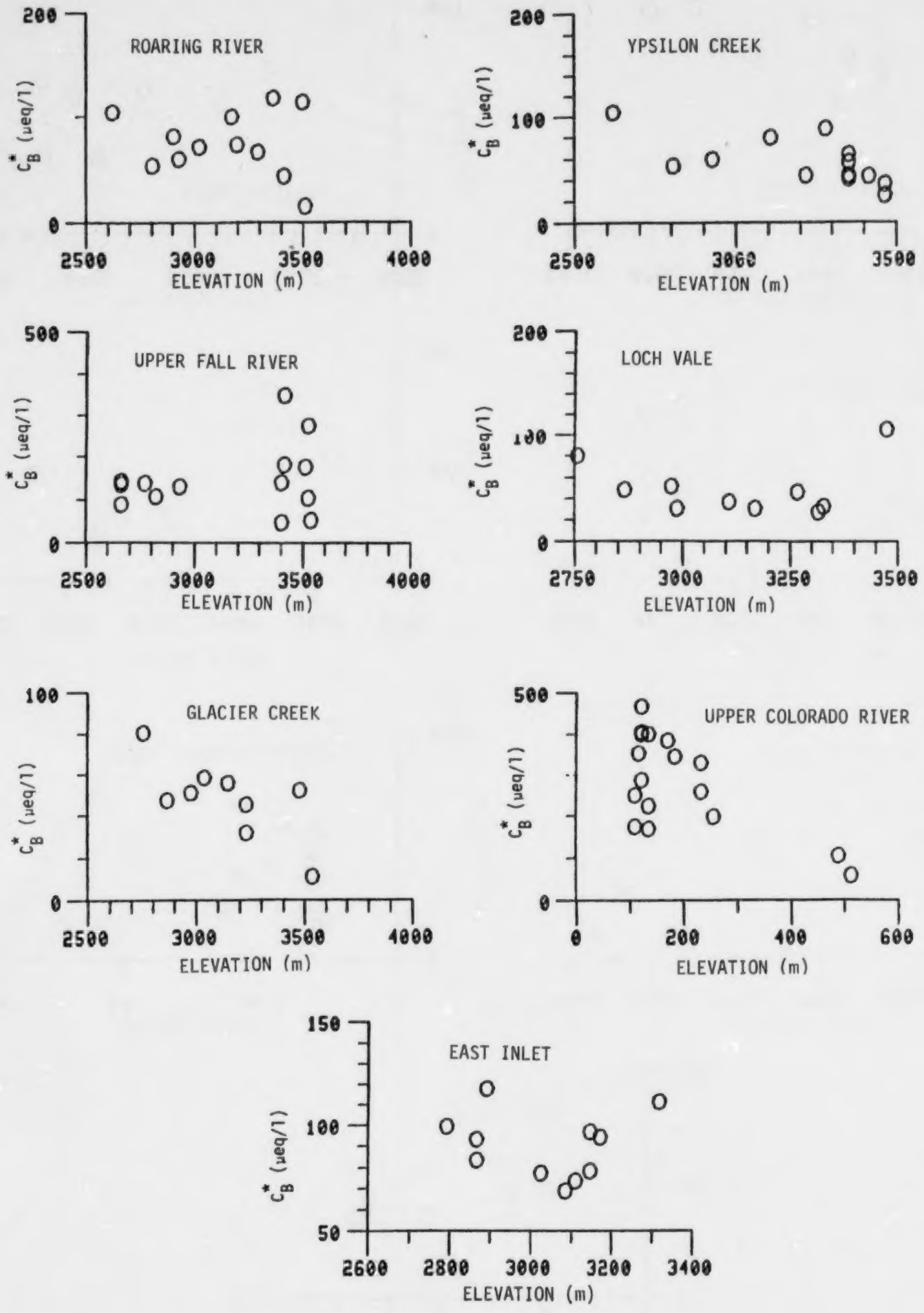


Figure 9. Graphs of excess base cations vs. elevation for subbasins in RMNP.

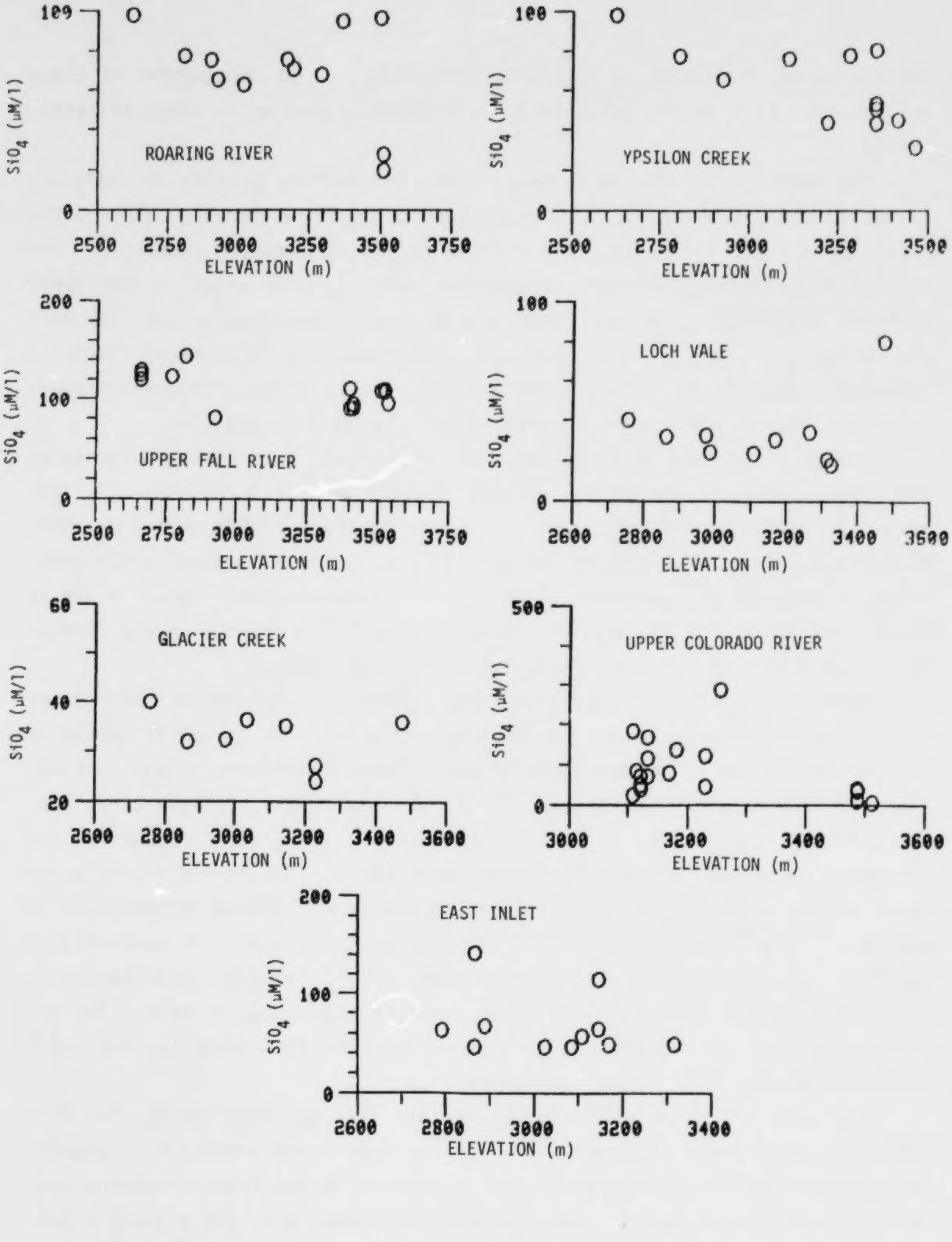


Figure 10. Graphs of silicate vs. elevation for subbasins in RMNP.

Surface water chemistry, particularly alkalinity is an integration of these mechanisms. As a result, alkalinity is frequently used as an index of sensitivity.

The geology in the Park ranges from Precambrian granite to tertiary intrusive and extrusive rocks. The difference in the weathering rates of the minerals in these formations is reflected by the streamwater chemistry. The highest concentrations of C_B^*, alkalinity, and silicate occur in the Upper Colorado River Basin, an area underlain by highly weatherable ash flow tuff and andesite. The C_B^* and alkalinity concentrations in Glacier Creek, a watershed underlain by Silver Plume granite, are an order of magnitude lower than those in the Upper Colorado River Basin (Tables 9 through 10).

R-mode factor analysis was used to investigate the relationships among the water chemistry variables and the bedrock and soil parameters. This method of analysis has been used by several authors (Dawdy and Feth 1967; Miller and Drever 1977a; Reeder et al. 1972) to interpret natural water chemistry in terms of its geochemical origin. In these analyses, factor analysis is used to reveal the geochemical processes responsible for the stream chemistry composition. A brief review of factor analysis follows.

Factor analysis is a statistical data reduction technique that rearranges the information contained in the correlation matrix for a set of variables into a smaller set of independent factors. These factors are linear combinations of the original variables. The first step in the analysis calculates the principal components, or factors that explain the greatest amount of the variances and co-variances in the correlation matrix. In the varimax solution used in this analysis, these principal components are rotated orthogonally to achieve a simple structure. This rotation produces a set of uncorrelated factors, so that the factor loadings (the extent to which each factor is associated with a particular variable) tend towards unity or zero. The resulting factors are interpreted as source variables accounting for the relationships between the original variables.

The data set from RMNP was split into two geologic groups for this analysis. One group represents all samples from areas underlain by granite and gneiss; the other represents the samples collected from watersheds containing tertiary volcanics. Each group was analyzed with and without a bedrock geology and soil parameter. The analysis of the stream chemistry alone allowed a larger sample size. Variables that had many zero values (K^* and NH_3) were not included in the analysis. All factors with eigen values greater than 0.51 are reported.

The results of the factor analysis of the granite and gneiss group show that four factors account for nearly 93% of the variance in stream water chemistry data (Table 11). The first factor, accounting for almost 50% of the variance, has high loadings for Na^*, Mg^*, SiO_4, and alkalinity. This factor is interpreted as an oligoclase and biotite weathering factor. These two minerals weather to kaolinite and vermicullite, respectively, releasing Na^{+1}, Mg^{+2}, SiO_4, HCO_3^{-1}, and a small amount of Ca^{+2}.

Table 11. R-mode varimax factor matrix of chemical data for 88 lake and stream samples underlain by granite and biotite gneiss and schist in Rocky Mountain National Park.

Variable	Factor			
	1	2	3	4
Na^{+1}	0.934	0.243	-0.185	-0.042
Mg^{+2}	0.827	0.346	0.092	-0.127
Ca^{+2}	0.325	0.919	0.144	0.068
Cl^{-1}	-0.031	0.082	0.112	0.975
NO_3^{-1}	-0.150	-0.025	0.945	0.078
SO_4^{-2}	0.259	0.437	0.609	0.479
SiO_4^{-4}	0.937	0.156	-0.029	0.180
Alk	0.538	0.656	-0.409	0.277
% of variance explained by factor	49.5	23.6	12.0	7.7
Cumulative % of variance	49.5	73.1	85.1	92.8

$$\underset{\text{(oligoclase)}}{Na_{0.7}Ca_{0.3}Al_{1.3}Si_{2.7}O_8} + 3.45\ H_2O + 1.3\ H_2CO_3 = 0.65\ \underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4}$$

$$+ 1.4\ H_4SiO_4 + 0.7\ Na^{+1} + 0.3\ Ca^{+2} + 1.3\ HCO_3^{-1}$$

$$3\ \underset{\text{(biotite)}}{K_2(Mg_3Fe_3)Al_2Si_6O_{20}(OH)_4} + 24\ H_2O + 18\ H_2CO_3 =$$

$$2\underset{\text{(vermicullite)}}{(Mg_3Fe_3)Al_3Si_5O_{20}(OH)_4 \cdot 8\ H_2O} + 6\ K^{+1} + 3\ Mg^{+2} + 3\ Fe^{+2} + 8\ H_4SiO_4 + 18\ HCO_3^{-1}.$$

The high percentage of the variance explained by this oligoclase and biotite weathering factor suggests that primary mineral weathering is one of the processes dominating stream water chemistry.

The second factor, accounting for 23.6% of the variance, is less easily interpreted. This factor loads heavily on Ca^{+2}, HCO_3^{-1}, and SO_4^{-2}. Ca^{+2} is not a major bedrock element, although a small percentage is contained in the oligoclase. Ca^{+2} in precipitation, however, is quite high and is also contributed to by dry deposition of dust and salts. This factor can be interpreted as a dry deposition factor, caused by the deposition of $CaSO_4$, and possibly $CaCO_3$.

The third factor, accounting for 12% of the variance, is an acid deposition factor. The high loadings of NO_3^{-1}, SO_4^{-2}, with an inverse relationship between the acid anions and alkalinity, represents the titration of lake and stream HCO_3^{-1} by anthropogenic acids. The fact that NO_3^{-1} loads higher on this factor suggests that HNO_3 may be a more important component of acid precipitation than H_2SO_4. The fourth factor, explaining 7.7% of the variance represents atmospheric deposition but does not appear to involve any buffering mechanisms.

The addition of percent unreactive rock (quartz + microcline) and percent soil organic matter (% O.M.) to the factor analysis results in a decrease in sample size and the loss of the acid deposition factor (Table 12). The first factor still represents oligoclase and biotite weathering, although Ca^{+2} loads

Table 12. R-mode varimax factor matrix of stream chemistry, % soil organic matter, and % unreactive rock for 40 lake and stream samples underlain by granite and biotite gneiss and schist in Rocky Mountain National Park.

Variable	Factor				
	1	2	3	4	5
Na^{+1}	0.958	-0.064	0.111	-0.066	0.164
Mg^{+2}	0.917	0.208	0.084	-0.090	-0.154
Ca^{+2}	0.558	0.727	0.354	-0.042	-0.048
Cl^{-1}	0.009	0.273	0.212	0.923	-0.082
NO_3^{-1}	-0.226	0.851	-0.212	0.286	-0.093
SO_4^{-2}	0.275	0.701	-0.172	0.543	-0.116
SiO_4^{-4}	0.917	0.053	0.024	0.238	0.168
Alk	0.741	-0.066	0.591	0.140	0.049
% O.M.	0.101	-0.107	0.064	-0.087	0.978
% rock	-0.118	0.085	-0.953	-0.112	-0.062
% of variance explained by factor	41.7	25.1	12.4	9.0	6.1
Cumulative % of variance	41.7	66.8	79.2	88.2	94.3

somewhat higher than in the previous analysis. The second factor still represents atmospheric deposition of $CaSO_4$ in dust and salts, although NO_3^{-1} also loads heavily on this axis. The third factor represents the inverse relationship between HCO_3^{-1} and unreactive rock, further evidence that primary mineral weathering plays a dominant role in stream chemistry. The fourth factor represents atmospheric deposition. The fifth factor represents % O.M., which is unrelated to any other variable, suggesting that soil ion-exchange processes play a very minor role in stream chemistry. The factor analysis of stream samples from areas underlain by tertiary volcanics shows that four factors account for 86.4% of the variance (Table 13).

The first factor, accounting for over 40% of the variance, indicates that the weathering processes in these watersheds are very different from those in

Table 13. R-mode varimax factor matrix of stream chemistry for 33 lake and stream samples underlain by tertiary intrusive bedrock in Rocky Mountain National Park.

Variable	Factor			
	1	2	3	4
Na^{+1}	0.122	0.911	-0.225	-0.076
Mg^{+2}	0.835	0.152	-0.264	0.129
Ca^{+2}	0.772	-0.410	0.138	0.115
Cl^{-1}	0.277	0.033	-0.025	0.955
NO_3^{-1}	-0.036	-0.219	0.946	-0.025
SO_4^{-2}	0.853	0.121	0.185	0.095
SiO_4^{-4}	0.006	0.884	-0.066	0.121
Alk	0.881	0.127	-0.184	0.247
% of variance explained by factor	40.3	26.5	10.0	9.6
Cumulative % of variance	40.3	66.8	76.8	86.4

the granite and gneiss areas. HCO_3^{-1}, SO_4^{-2}, Ca^{+2}, and Mg^{+2} all load heavily on this factor, representing the weathering of mafic minerals low in silica, as well as the dissolution of $CaSO_4$ in the Pierre shale of the Upper Colorado Basin. The second factor explains 26.5% of the variance and loads heavily on Na^{+1} and SiO_4^{-4}. This factor can be described as oligoclase weathering. The third and fourth factors, accounting for 19.6% of the variance, each explain a single variable and cannot be interpreted in terms of buffering mechanisms. The addition of soil and bedrock parameters in this analysis reduced the sample size to 16 observations, too few to be used with factor analysis.

The results of the analyses of the two geologic groups suggest that primary mineral weathering is the major mechanism underlying the stream chemistry. The weathering of oligoclase and biotite, the dry deposition of $CaSO_4$ dust, and the titration of bicarbonate by anthropogenic acids appear to be the major geochemical processes in the watersheds underlain by granite and biotite gneiss and schist. An assemblage of low-silica, high-sulfate minerals appears to be responsible for much of the stream chemistry in areas underlain by tertiary intrusives. Oligoclase weathering plays an important role in the chemistry of these watersheds, while no evidence of acid titration of bicarbonate was found.

Discriminant function analysis (DFA) was used to examine the differences in stream chemistry between the areas underlain by tertiary volcanic bedrock and those surrounded by granite and biotite gneiss and schist. DFA distinguishes between two populations on the basis of observations of multiple variables. DFA may also be used to classify data on the basis of observed variables. In this two-group discriminant analysis, one discriminant function is formulated by the analysis. This function is a linear combination of the measured variables, i.e.,

$$L = B_1X_1 + B_2X_2 + . . . + B_nX_n \quad ,$$

where L is the discriminant function, X_n are the measured variables, and B_n are the discriminant function coefficients. The discriminant function L is formulated to achieve the maximum discrimination between the two groups; i.e., the variance in L within each group is much less than the variance in L between the two groups. The discriminant function analysis also indicates which variables differ most between the two groups. The correlation between the measured variables and the discriminant function (ranges between -1.0 and +1.0) gives an indication of the importance of that variable in differentiating between the two groups.

In this application, DFA is used to differentiate between the two major geologic groups (tertiary volcanics vs. granite and biotite gneiss and schist) on the basis of the water chemistry parameters. The results of the DFA show that the two groups are significantly different (Table 14). The correlations between the water chemistry parameters and the discriminant function show that alkalinity, Mg^{+2}, Ca^{+2}, and SO_4^{-2} are the parameters responsible for the difference between the two geologic groups. These are the same variables that make up the first factor in the factor analysis of the tertiary volcanic group. This result is consistent with the belief that the differences in stream chemistry between the two geologic groups are caused by mineral weathering processes. The reclassification of the data set on the basis of

Table 14. Discriminant analysis of surface water chemistry from 117 lake and stream samples from Rocky Mountain National Park.

Variable	Correlation
Alkalinity	0.854
Mg^{+2}	0.823
Ca^{+2}	0.615
SO_4^{-2}	0.558
Cl^{-1}	0.348
SiO_4^{-4}	0.337
Na^{+1}	0.297
NO_3^{-1}	-0.173

the discriminant function resulted in a 95.7% correct classification (Table 15).

The results of this analysis show that water chemistry characteristics of areas underlain by similar bedrock geology can be estimated on the basis of

Table 15. Reclassification results.

Actual group	No. of cases	Predicted group membership	
		1	2
Group 1 (granite and gneiss)	88	88 100.0	0 0
Group 2 (tertiary intrusives)	29	5 17.2	24 82.8

Percent of grouped cases correctly classified = 95.73

geologic type. Areas with tertiary intrusive rocks present in their catchments can be expected to have significantly higher alkalinity, magnesium, calcium, and sulfate than areas underlain by granite and gneiss.

Summary. The chemical composition of the waters in RMNP is a product of the interactions between atmospheric deposition and bedrock geology and surficial materials. Soils play a minor role. The previous discussions show that bedrock mineralogy, atmospheric deposition, and elevation all significantly affect the stream chemistry in RMNP.

Primary mineral weathering appears to be the dominant mechanism determining the concentrations of base cations, silica, and alkalinity throughout the park. Factor analysis shows that the primary mineral weathering of oligoclase and biotite account for almost 50% of the variance in stream chemistry in areas underlain by granite and biotite gneiss and schist. In areas that contain tertiary volcanic bedrock, the mineral weathering of mafic minerals, sulfur-bearing minerals, and oligoclase account for more than 50% of the variance in stream chemistry. Soils appear to have little effect on stream chemistry. The soils are highly permeable, low in clays, and very thin. Soil organic matter accounts for most of the soil CEC, but % O.M. does not form a factor with any of the stream chemistry variables.

Alkalinity, C_B^*, and sulfate are inversely related to elevation in the Glacier Creek, Loch Vale, Ypsilon Creek, Roaring River, and East Inlet subbasins. This is a result of the deeper glacial till (larger flow path) and gentle gradients (larger residence time) at lower elevations.

Atmospheric deposition is the primary source of chloride and nitrate in the streams of RMNP. Atmospheric deposition is also the primary source of sulfate in RMNP waters, with the exception of the Upper Colorado and Upper Fall River basins, where the weathering of sulfur-bearing minerals is a source of sulfate. Chloride and sulfate are relatively constant with elevation, while nitrate concentrations are highest above the timberline, where biological activity is lowest. Atmospheric deposition is also a significant source of stream water C_B, a result of the deposition of airborne dust and salts from the dry, windy regions upwind of RMNP.

Discriminant function analysis of the water chemistry data shows that bedrock mineralogy can be used to estimate the water chemistry of RMNP. Bedrock mineralogy will be used in later sections to assess the sensitivity (as measured by alkalinity) of similar geologic areas in the central Rocky Mountain region.

Alkalinity (Sensitivity) of RMNP Lakes and Streams

An area's ability to neutralize acidic deposition through interactions with bedrock and surficial geology determines its vulnerability to acidic deposition. The lithological characteristics of a watershed, combined with its water chemistry data, provide the basis for assessing the area's sensitivity to acid rain. Alkalinity, an integrator of watershed buffering mechanisms, is often used as an index of sensitivity. Hendrey et al. (1980) define sensitive waters as those with alkalinities lower than 200 μeq/l, a level low enough to be neutralized by acidic deposition and runoff. Using this definition, we find that much of the RMNP is sensitive to acidic deposition.

As we have seen in the previous sections, the sensitivity of the watersheds in RMNP is primarily determined by the bedrock geology of the watersheds. Within each watershed, elevation may be used to further divide the basins into areas of different sensitivities. The classification scheme used for assessing the sensitivity of RMNP to acidic deposition defines sensitive waters as those with alkalinities less than 200 μeq/l, while waters with alkalinities less than 100 μeq/l will be considered very sensitive. Lakes and streams with alkalinities below 50 μeq/l are classified as extremely sensitive. Following this classification scheme, we have evaluated the sensitivity above and below 3300 m in each subbasin (Figure 11). The results show the following classifications:

Extremely sensitive (alkalinity ≦ 50 μeq/l)	Glacier Gorge Ypsilon Creek
Very Sensitive (50 ≦ alkalinity ≦ 100 μeq/l)	Roaring River Upper East Inlet
Sensitive (100 μeq/l alkalinity ≦ 200 μeq/l)	Lower East Inlet High elevations of Upper Fall River
Nonsensitive (alkalinity ≧ 200 μeq/l)	Lower elevations of Upper Fall River Upper Colorado River

Current Acidification Status of RMNP

Researchers have observed acidic deposition in the Rocky Mountains since 1967 (Lewis and Grant 1979). These authors report a decrease in stream

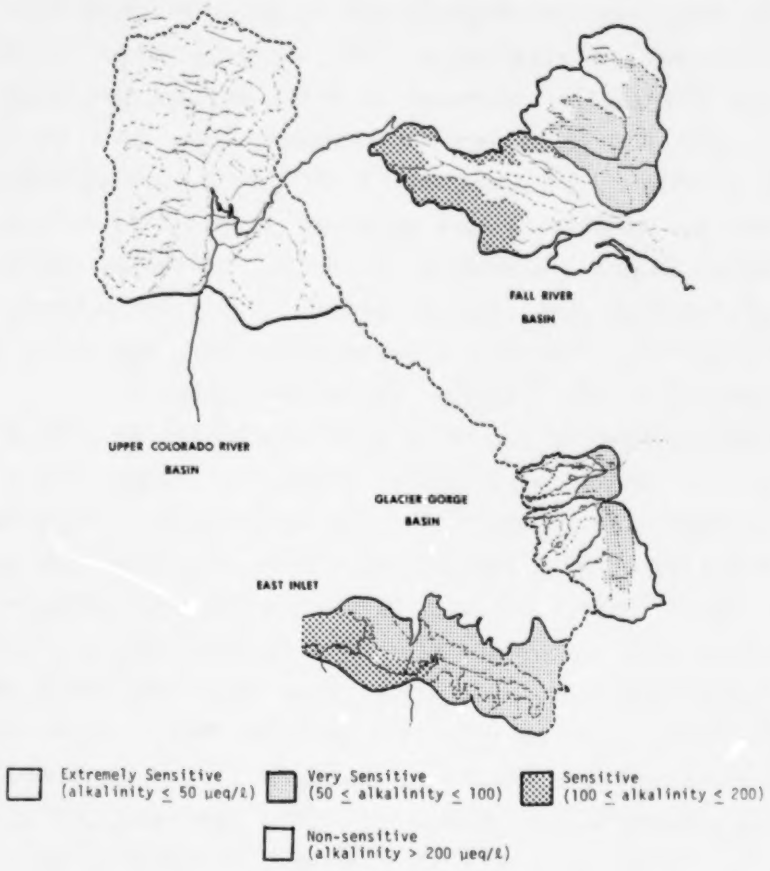

FALL RIVER BASIN
UPPER COLORADO RIVER BASIN
GLACIER GORGE BASIN
EAST INLET
Extremely Sensitive (alkalinity ≤ 50 μeq/ℓ)
Very Sensitive (50 ≤ alkalinity ≤ 100)
Sensitive (100 ≤ alkalinity ≤ 200)
Non-sensitive (alkalinity > 200 μeq/ℓ)

Figure 11. Spatial distribution of sensitivity in RMNP (see map Figure 1).

bicarbonate in the Como Creek watershed of north-central Colorado over a 150-week period. This record, however, is too short to be considered evidence of increasing acidification. Lewis (1982) reports an average decrease in alkalinity from 22 mg/l to 18 mg/l as CO_2 [equivalent to a decrease from 1000 µeq/l to 818.2 µeq/l (Lowenthal and Marias 1978)] for 104 lower-elevation lakes surveyed by Pennak from 1938-1942 and resurveyed by Lewis in 1979. Although Lewis attributes this loss to acidic deposition, the concurrent decrease in total residue suggests that hydrologic variability is responsible for this decrease in alkalinity. The high discharge in 1979 (~30% above average) and the similar decrease in total residue and alkalinity (22% for alkalinity, 21% for total residue) suggests that this decrease is mainly caused by dilution. In addition, a 180 µeq/l loss of alkalinity is much greater than any alkalinity loss observed in acidified regions of the northeastern United States (Hendrey et al. 1980). Although several areas in the Rocky Mountains have been shown to be potentially sensitive to acidic deposition (Harte et al., submitted; Dodson 1981; Turk and Adams 1983), no convincing evidence of acidification has been presented.

At present, RMNP is receiving much less acidic deposition than acidified regions in the northeastern United States. A comparison of the (volume-weighted average) concentrations of the major ions in precipitation show that the precipitation at RMNP contains much less acid than that at Hubbard Brook (Table 16) (NADP 1982). During 1981 the average precipitation pH at RMNP was 5.07, compared with an average of 4.33 at Hubbard Brook. Sulfate concentrations at Hubbard Brook are also higher than those observed at RMNP (48.9 µeq/l at Hubbard Brook, compared with 35.0 µeq/l at RMNP), while the C_B concentration at RMNP is more than double the concentration at Hubbard Brook. However, the nitrate concentrations observed at these two locations are very similar, 21.9 µeq/l at RMNP, compared with 21.2 µeq/l at Hubbard Brook. These results suggest that much of the acidity observed in RMNP precipitation may be caused by nitrate, while the sulfate is probably a combination of anthropogenic emissions of sulfur dioxide, along with sulfate associated with C_B from airborne dust and salts.

Since no historical water-chemistry data are available for RMNP, we base our assessment of its present acidification status on the current composition of its waters. According to electroneutrality conditions:

Table 16. Comparison of Rocky Mountain National Park and Hubbard Brook precipitation chemistry (National Atmospheric Deposition Program 1982).

	RMNP		Hubbard Brook	
Ion	Vol. wt. average (μeq/l)	Yearly deposition (meq/m²)	Vol. wt. average (μeq/l)	Yearly deposition (meq/m²)
H^+	8.6	3.0	46.5	71.1
SO_4^{-2}	35.0	12.2	48.9	75.8
NO_3^{-1}	21.9	7.5	21.2	32.5
Cl^{-1}	4.9	1.7	5.3	8.3
Ca^{+2}	21.9	7.7	6.5	10.4
Mg^{+2}	8.1	2.9	3.6	5.6
K^{+1}	5.8	1.1	0.4	0.7
Na^{+1}	3.0	2.1	5.1	7.9

$$C_B = HCO_3^{-1} + SO_4^{-2} + NO_3^{-1} + Cl^{-1} - H^{+1} - \text{metals}^{+n} \quad .$$

Under acid rain conditions, anthropogenic acids (H_2SO_4 and HNO_3) reduce the relative concentration of alkalinity in this equation by titration. We can use the "excess" concentration of base cations to provide an estimate of the alkalinity replaced by acid anions (i.e., amount of acidification). After correcting for the deposition of salts and excluding H^+ and metals, which are negligible at the pH of water in RMNP, the ion balance equation is reduced to:

$$C_B{*} - HCO_3^{-1} = C_A{*} \quad ; \quad \text{where } C_A{*} = NO_3^{-1} + SO_4^{-2}{*} \ .$$

The results of these calculations for the most sensitive watersheds (Glacier Creek, Loch Vale, East Inlet, and Ypsilon Creek) show that these waters have, at the most, suffered a small loss of alkalinity (Table 17). It

Table 17. Calculation of acidification status for Rocky Mountain National Park watersheds according to ion balance considerations.

Watershed	C^*_B (μeq/l)	–	Alkalinity (μeq/l)	=	Calculated Acidification (μeq/l)
Roaring River	72.3		74.4		None
Ypsilon Creek	56.2		48.0		8.2
Upper Fall River	155.2		180.5		None
Andrews Creek	57.3		38.8		18.5
Loch Vale	47.9		41.2		6.7
Glacier Creek	47.6		40.3		7.3
Upper Colorado River	280.1		319.0		None
East Inlet	91.5		85.5		6.0

is so small that the combined effect of analytical error and the error associated with the correction for atmospheric salts is probably as large as the calculated acidification. The Upper Colorado River, Upper Fall River, and Roaring River show no evidence of acidification.

A similar method for evaluating the current acidification status of low ionic strength lakes is the "predictor nomograph" developed by Henriksen (1980). This model was empirically derived to evaluate the impact of increased acid precipitation on lakes in Norway but may also be used to assess current acidification status. The model is based on electroneutrality conditions, assumes no increase in weathering of base cations, and considers atmospheric deposition to be the only source of SO_4^{-2}. The nomograph is a plot of the "excess" Ca^{+2} and Mg^{+2} vs. "excess" SO_4^{-2} in lake waters. "Excess" means nonmarine in origin. The lake SO_4^{-2} concentrations have been correlated with pH and SO_4^{-2} concentrations in rain by a regression analysis of data from

719 Norwegian lakes. The graph has been divided into three sections to represent three stages of acidification. The first stage represents waters that still contain enough alkalinity to buffer incoming acid precipitation, "bicarbonate lakes." The second stage of the nomograph is representative of "transition lakes." These waters experience rapid fluctuations in pH because of their low alkalinities. The third stage of acidification are the "acid lakes", characterized by low pH and increased aluminum concentrations. The nomograph is used to predict acidification status by plotting precipitation pH or excess lake $SO_4^{-2}*$ with "excess" Ca^{+2} + Mg^{+2} in µeq/l. This simple empirical model has been successfully applied to lakes in the Adirondack, Canada, Scandinavia, and Scotland (Wright et al. 1980). Although there are some differences between these areas and RMNP (notably the soils), the similarity of geochemical processes should allow our use of the nomograph with some changes.

We have modified the Henriksen nomograph to use as a tool to evaluate the current and future effects of acid rain in the Rocky Mountains. Ca^{+2} and Mg^{+2} are the major base cations in Henriksen's study area, while Na^{+1} + Mg^{+2} are the dominant cations in RMNP. As a result, we have replaced the "excess" Ca^{+2} + Mg^{+2} used by Henriksen as the y axis in the nomograph with C_B*. As previously stated, RMNP receives minimal sea-salt deposition but does receive atmospheric deposition of salts and dust. C_B* is our best estimate of "excess" base cations.

Since much of the acid deposition in this region is in the form of HNO_3 (NADP 1982; Lewis and Grant 1979; Kelley and Stedman 1980), we have further modifed the Henriksen nomograph by using C_A* ($SO_4^{-2}*$ + $NO_3^{-1}*$) as the x axis in the nomograph. The waters in RMNP contain a large indeterminate "natural," or background, concentration of SO_4^{-2}, a result of the atmospheric deposition of dust and salts. We expect that only part of the SO_4^{-2} in RMNP lakes is the result of acid deposition. Almer et al. (1978) estimate the background concentration of SO_4^{-2} in Scandinavian lakes to be 20-60 µeq/l. To estimate acidic deposition, we will use Almer's lowest estimate of background SO_4^{-2} to calculate a maximum "excess" $SO_4^{-2}*$:

$$SO_4^{-2}* = SO_4^{-2} - 20.0\ \mu eq/l \quad .$$

In this scenario, $C_A* = NO_3^{-1}* + SO_4^{-2}*$.

Plotting this information on the nomograph shows that most of the lakes in RMNP can be classified as "bicarbonate", while a few approach the "transition" stage (Figure 12).

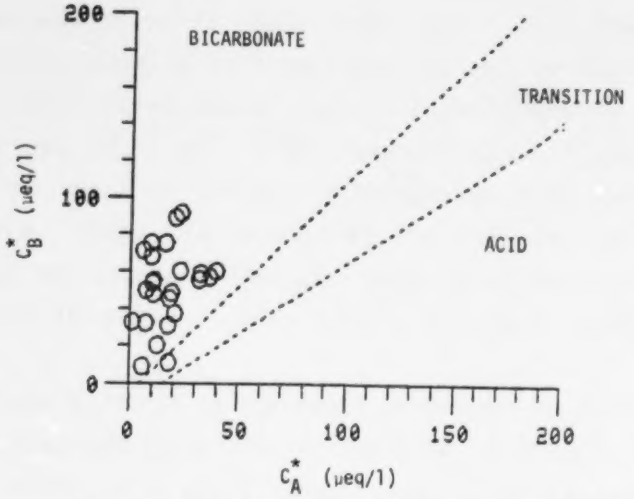


Figure 12. Status of 23 lakes in RMNP.

The high cation concentrations in RMNP precipitation indicate that the park is undoubtedly receiving "natural" deposition of sulfate in the form of salts and dust from the surrounding arid regions. However, the low pH of Rocky Mountain precipitation indicates that some of the sulfate and nitrate is being deposited as acid deposition. It is likely that the waters in RMNP have suffered some loss of alkalinity because of acidic deposition, but this loss (a maximum of ~10 μeq/l) is minor compared with that experienced in lakes in the northeastern United States.

Future Impacts of Acidic Deposition

As we have seen in the previous sections, the Central Rocky Mountains are extremely sensitive to acidic deposition but have as yet suffered little or no acidification on a regional basis. An increase in acidic deposition could have some serious consequences. The development of major coal and oil shale resources upwind of this region and the subsequent increase in acidic deposition could have a serious impact on the surface water acidity in the region. Using the Henriksen predictor nomograph described in the previous section, we can estimate the best- and worst-case consequences of an increase in the current rate of deposition, to that experienced in the northeastern United States. The scenario for increased acidic deposition in RMNP assumes a decrease in precipitation pH to that experienced in the northeastern United States. This involves an increase in H^+, from pH 5.1 to 4.3, which will be accompanied by an increase in lake C_A^* of approximately 80 μeq/l.

In the worst-case scenario, the increase in acidic precipitation will not increase C_B^* but will only result in decreased alkalinity. Using our estimate of current C_A^*, ($SO_4^{-2*} + NO_3^{-1*}$ - 20 μeq/l) a worst-case prediction using the nomograph indicates that most of the lakes in RMNP will reach "acid" status, while the remainder will be classified as "transition" lakes (Figure 13).

In the best-case scenario, the increase in acidic deposition will be accompanied by an increase in C_B^* of 0.4 μeq/l per 1.0 μeq/l C_A^*. This increase in C_B^* with increased acidic deposition was empirically calculated by Henriksen using data from low-alkalinity lakes in several areas. The best-case scenario predicts that a few lakes will remain "bicarbonate," the majority will become "transition" lakes, and several lakes will still reach "acid" status (Figure 13).

Henriksen's evaluation of data sets from Norway, Sweden, Canada, and the United States shows that there is an increase in base cation weathering with acid rain for some, but not all watersheds. Increases in C_B will probably occur in regions that have soils with high levels of exchangeable bases. When these areas receive acidic deposition, base cations on the soil exchange sites will be replaced with H^+ by mass action, increasing surface water C_B^*. In regions with poorly buffered soils, the increase in C_B^* with acid deposition will be smaller, since fewer exchange sites contain base cations for ion exchange. Other researchers have shown that the rate of primary mineral weathering in areas with granitic and metamorphic rock does not increase under acid rain conditons (Johnson et al. 1981). The low ion-exchange capacity of the soils in RMNP and the bedrock composition indicate that the increase in C_B^* with increased acidic deposition in RMNP will be low and that with increasing acidic deposition many of the lakes will shift from bicarbonate towards acid status.

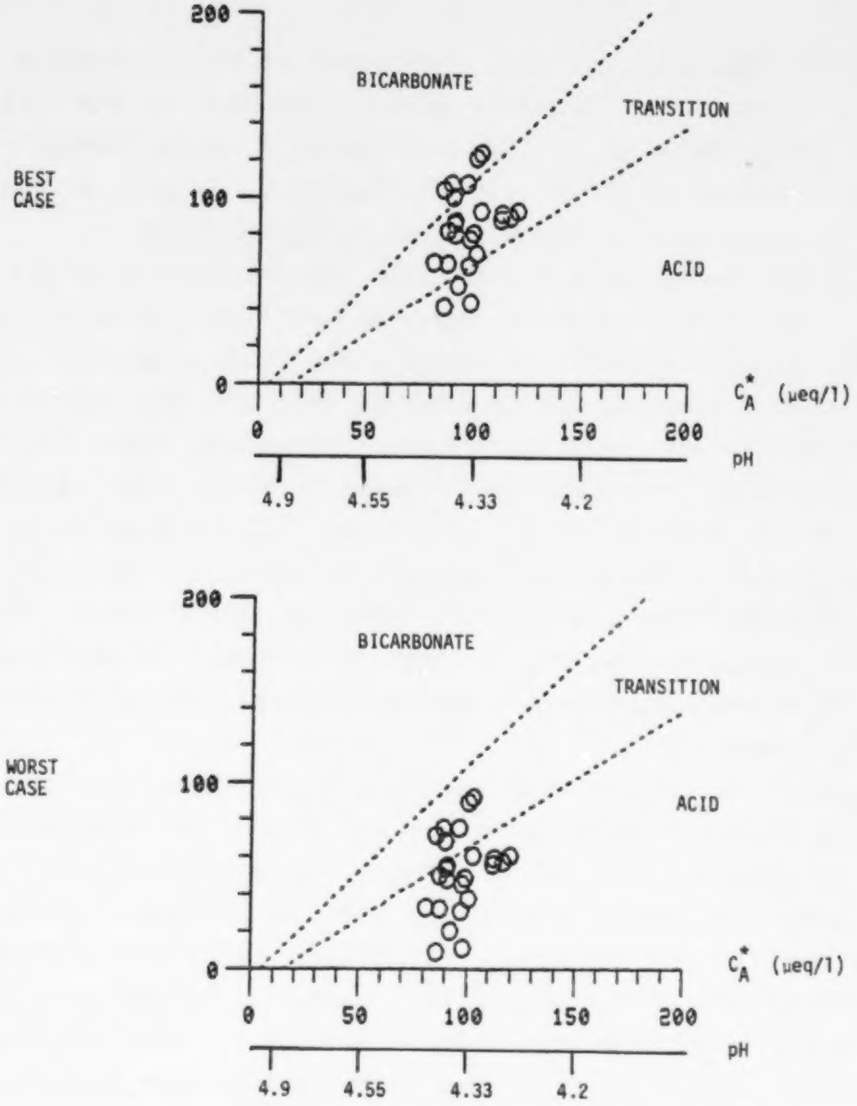


Figure 13. Predictor nomographs projecting the best and worst-case estimates of the effects of increased acidic deposition on lakes in RMNP.

YELLOWSTONE NATIONAL PARK

INTRODUCTION

Located in northwestern Wyoming at the northern edge of the potentially sensitive Rocky Mountain region, Yellowstone National Park (YNP) is characterized by extreme variability in geology, geologic history, and water chemistry. The 3,742 square mile park contains four large lakes (Yellowstone, Shoshone, Lewis, Heart), and numerous streams, rivers, and small back-country lakes, a number of which support trout populations. As in the case of Rocky Mountain National Park, the general objectives of the study in Yellowstone National Park were to determine the sensitivity of waters to acidification by current levels of acid precipitation and to determine whether this will affect fish populations. The accomplishment of these objectives is based primarily on the evaluation of a water chemistry data base developed over the last 30 years.

DESCRIPTION OF GEOLOGY

Topographically, Yellowstone is dominated by a high plateau from about 1800 to 2800 m in altitude. The plateau is bounded on three sides by mountain ranges: the Gallatin and Beartooth mountains to the north, the Absaroka range to the east, and uplands from the Teton and Washakie ranges in the south (Cox 1973). The continental divide transects the park along the southwestern edge--approximately 20 percent of the park area drains west into the Snake River basin, and 80 percent drains east into the Missouri River drainage.

Cox (1973) divided Yellowstone into seven hydrologic units following geologic and geographic boundaries. These are: Rhyolite plateau (RP), Gallatin (GT), Beartooth (BT), Absaroka (AB), Falls River (FR), Snake River (SR), and West Yellowstone (WY) (Figure 14). The plateau area (RP) is underlain by Tertiary and Quaternary rhyolite flows, while north and south of the

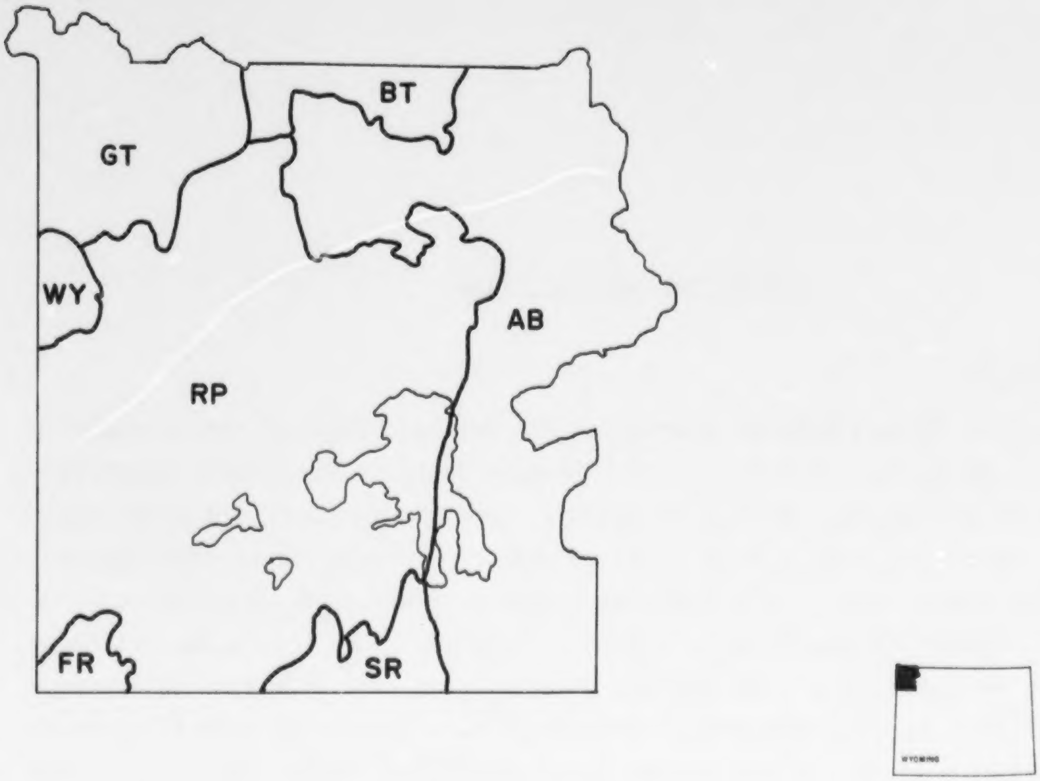


Figure 14. Regional-geological map of Yellowstone National Park (adapted from Cox 1973). (AB) Absaroka region is predominantly andesitic lava flows and breccia, with basalt, and some occurrence of rhyolite, sandstone, and limestone; (BT) Beartooth region is a mix of Precambrian granites, Paleozoic and Mesozoic sandstones and shales, and Tertiary/Quaternary volcanics; (FR) Falls River region is Quaternary rhyolite and basalt, frequently overlain by alluvial and glacial deposits; (GT) Gallatin region is Precambrian granites, Paleozoic and Mesozoic limestones, sandstones, and shales, Tertiary/Quaternary volcanics; (RP) Rhyolite plateau region is predominantly Tertiary and Quaternary rhyolite flows; (SR) Snake River region is Paleozoic and Mesozoic limestones, sandstones, and shales, with some outcroppings of Tertiary rhyolite and andesite; (WY) West Yellowstone region is rhyolite overlain by alluvial, glacial, and lacustrine deposits.

plateau are a heterogeneous, heavily faulted mix of PreCambrian granites, Paleozoic and Mesozoic limestones, shales, and sandstones, and more recent (Tertiary, Quaternary) volcanic deposits (GT, BT, SR). Between the plateau region and the Gallatin range along the extreme western park border lies a series of deep (c.200 feet) alluvial and glacial deposits underlain by volcanic rocks (WY). East of the plateau is a mountainous area composed mostly of Tertiary andesitic lava flows and breccia (AB), while basalt flows occur in the extreme southwest (FR).

Rhyolite, located in the southwest and central portion of the park as well as in outcroppings throughout the rest of the region, is clearly the dominant bedrock type. Extremely rich in silica, rhyolite is chemically nearly equivalent to granite (Bryan 1979). Although fairly uncommon through the world, nearly all geysers are associated with rhyolite formations, since the rock provides the pressure-tight "piping" necessary for geyser creation. The rhyolite in Yellowstone consists primarily of lava and welded tuff with assorted deposits of breccia, ash, and glass. All of the types are chemically similar, although tuff may be slightly more weatherable than lava due to differing extrusion and deposition processes (Herzog 1982; Cox 1973). Rhyolite may be altered by hot water and gas near hot springs.

Weatherability of the bedrock types may be roughly ranked by chemical characteristics as follows (Herzog 1982 and personal communication; Loughnan 1969):

low	granite, rhyolite
↓	ash flow tuff
↓	metamorphics--biotite gneisses and schists
↓	andesite
↓	basalt
high	limestones, shales, sandstones

In addition to a heterogeneous geology, the park bears the ubiquitous remains of three major glaciations originating in the Absaroka Range and Beartooth Mountains. Most of the current park deposits date to the last major glaciation, the Pinedale (10-30,000 years b.p.), which covered 90% of the park. Abundant till and kame deposits throughout Yellowstone attest to the influence of these geologic events.

DETERMINATION OF SURFACE WATER CHEMISTRY

Surface water quality studies in Yellowstone date to as early as the 19th century, when Gooch and Whitfield (1888) published the first chemical data for Yellowstone Lake. Until comparatively recently, however, surveys concentrated on the four largest lakes, all of which are chemically insensitive to acidification by acid precipitation (alkalinity >200 µeq/l). Chemical surveys of the more vulnerable back country lakes were initiated in 1964 by the Yellowstone National Park Fishery Management Investigation, and continue to the present.

Field pH and alkalinity were measured with a Hach Field engineers kit until 1974, when the Hellige kit was introduced for pH measurements. During 1969 and 1970, laboratory analysis of water samples were performed by the Bureau of Indian Affairs Soil Laboratory in Gallup, New Mexico. (No laboratory analyses were performed from 1971 to 1973.) Beginning in 1974 and continuing to the present, lab analysis of samples was performed by Orlando Laboratories, Orlando, Florida. Almost all samples were refrigerated, mailed within two days, and processed within a week. Analytical methods used by both labs were in accordance with then-current Standard Methods for the Analysis of Water and Wastewater.

All pH values reported in this study were obtained colorimetrically in the field. Burns et al. (1981) found that measurements from a Hellige kit agreed to within 0.15 pH unit with potentiometric values, although Pfeiffer and Festa (1980) report a systematic bias expressed by the following relationship:

$$\text{Old (Hellige)} = 0.6639\ (\text{pH meter}) + 2.534$$

$$r^2 = 0.91$$

All alkalinities reported were determined in the laboratory by colorimetric titration to pH 4.6 (Standard Methods #403), except during the years 1965-1966 and 1971-1973, when only field measurements were taken. Field alkalinities were determined colorimetrically during this period with the Hach field engineers kit (Model DR-EL or AL-36-P). Colorimetric titrations do overestimate alkalinity by the amount of free hydrogen ion in solution at the endpoint; at titration to pH 4.6, this is 25 µeq/l alkalinity for all samples. Analytical methods for major cations and anions are given in Table 18 for the years 1969-1970 and 1974-present. The current (15th edition) Standard Methods is referenced in Table 18, although it is assumed that the most recently available version was followed for historical samples. Quality assurance was determined by calculating ion balances for all those lakes with complete

Table 18. Analytical methods, Yellowstone National Park.

Parameter	Method, 1969-70	Method 1974-present
Alkalinity	Standard method #403. Colorimetric titration using phenolphthalein (end point pH 8.3) and methyl orange (end point pH 4.6) indicators	
Calcium	Standard method #306C EDTA titrimetric	Hach Method, p. 122 Titrimetric
Magnesium	Standard method #313C; calculation from EDTA hardness	
Sodium	Standard method #325B; flame photometric	
Potassium	Standard method #322B; flame photometric	
Sulfate	Standard method #427A Gravimetric with ignition residue	EPA #375.4 Turbidimetric
Chloride	Standard method #407A; argentometric	

(Standard methods 1980; EPA 1979; Hach 1978)

chemical records (see Appendix D). Lakes with ion balances with absolute values less than or equal to 20% are considered usable for the purposes of this study.

The 106 lakes discussed in this report represent a significant sample of all the lakes in YNP. All the major lakes have been surveyed, including those of special recreational or scientific significance. Every region, major geological formation and geochemical type of lake has been sampled in the survey. Because of its large size, Yellowstone Lake was surveyed at four different locations in the lake. The chemistry of the lakes not surveyed may be inferred by the chemistry of neighboring surveyed lakes.

RESULTS AND DISCUSSION

As stated in the introduction, the RMAS project relied on available data from Yellowstone National Park. There was thus no opportunity to design a sampling program to test hypotheses relating lake and stream sensitivity to elevation, soils, and geology, as was the case for Rocky Mountain National

Park. YNP data were available for lakes only, and there had been no attempt to obtain data on complete watersheds or to relate sampling locations to elevation, soils, or geology. In addition, water chemistry data were obtained over the years using different analysis methods and samples were analyzed by different laboratories. All of these factors made it impossible to carry out the extensive evaluations reported in the chapter for Rocky Mountain National Park. The evaluation of information from YNP focuses on sensitivity or alkalinity, which are the critical factors in assessing the health of fish populations. In addition, the general YNP findings can be compared with those from RMNP to verify the ability to extrapolate results from one region to another.

Lake Alkalinities (Sensitivities)

A spatial sensitivity map, using alkalinity as an index of vulnerability to acidification, was created for the park with recent alkalinity data (Figure 15). The selection of alkalinity as the best index of sensitivity to acid precipitation is based on its physical significance as the emergent sum of many acid-neutralizing processes occurring in the watershed, and its well-documented relation to pH (Henriksen 1979). Using Hendrey et al.'s (1980) convention, those lakes with alkalinity values <200 μeq/l are considered potentially sensitive to long-term inputs of acid precipitation. For Yellowstone, lakes with alkalinity values reported as 230 or less are considered in this category, due both to the underestimation implicit in colorimetric titrations, and to account for imprecision in the analysis. One fourth (30 of 106) the surveyed lakes may be considered "sensitive" by this criterion. Thirteen of these lakes show alkalinities ≤100 μeq/l, although at least six are influenced by thermal springs or humic acids (YNP Fishery Management Investigations reports).

Excluding those lakes that are located in the midst of major geothermal areas, the lowest alkalinity measured was 40 μeq/l. Yellowstone lakes on the average apparently show considerably greater levels of alkalinity than those determined for Rocky Mountain National Park lakes, probably due primarily to differing geology between the two areas (most of the Rocky Mountain National Park samples are collected in areas underlain by Precambrian granites and metamorphic rocks). Of the four basins considered in the RMNP study, the Upper Colorado River watershed is geologically the most similar to Yellowstone,

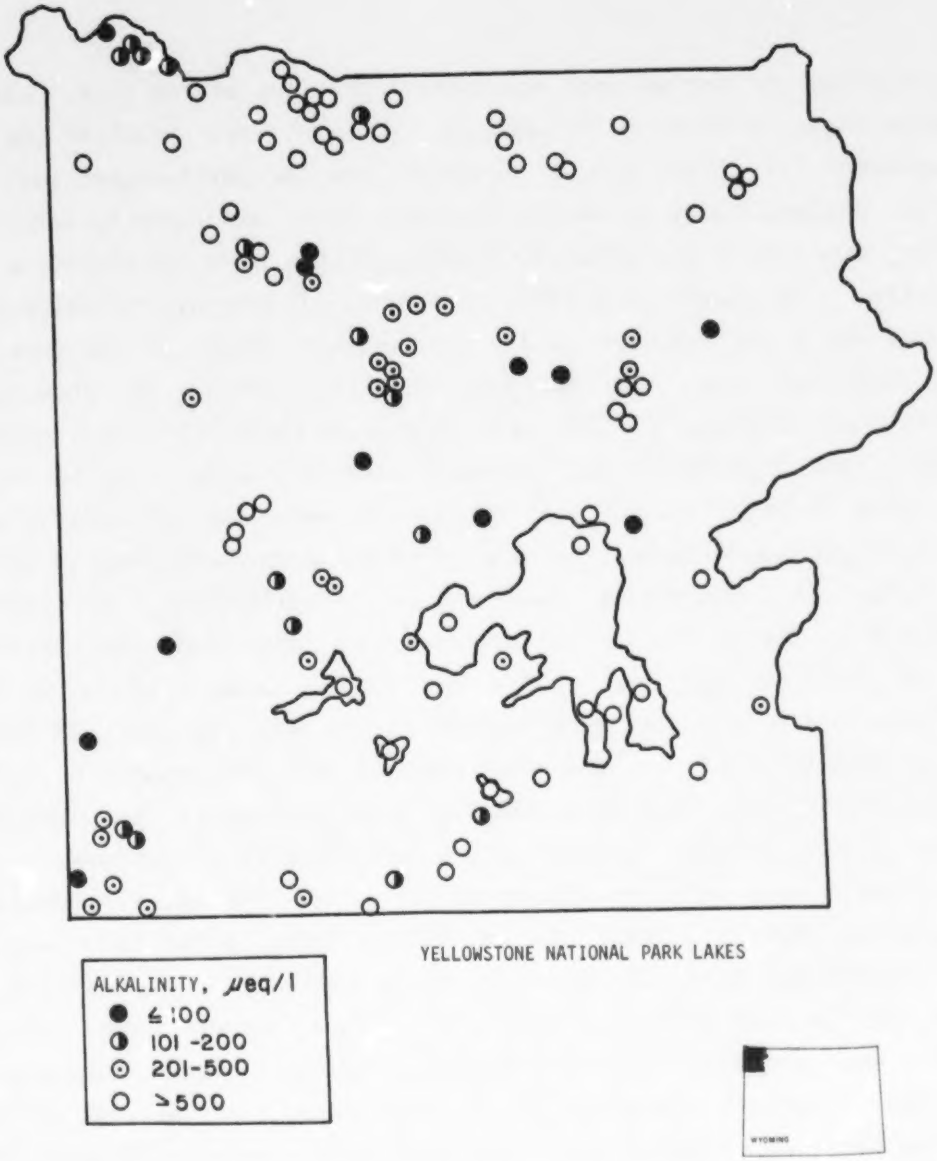

YELLOWSTONE NATIONAL PARK LAKES
ALKALINITY, μeq/l
● ≤100
◑ 101 -200
⊙ 201-500
○ >500
WYOMING

Figure 15. Alkalinity map, Yellowstone National Park.

Yellowstone, as it shows a significant (ca. 8%) accumulation of volcanic rocks. This watershed shows the highest alkalinity and pH values of the RMNP study sites [average alkalinity equals 248 μeq/l (this study)].

Although the low-alkalinity (<230-μeq/l) lakes in Yellowstone show no clear geographical (spatial) patterns, a geological pattern is evident. Most occur within the large rhyolite flow which rises from the southwest and spreads along the central-west and central portions of the park. Lakes with slightly higher alkalinity values (ca. 300 µeq/l) are found in the extreme southwestern Fall River basalt formation and the northwestern part of the rhyolite plateau. Most of the northernmost lakes, dominated by andesites and basalts, show very high alkalinity (>1000 µeq/l) and are not sensitive to acid deposition. The exception to this is a group of five high-altitude lakes of the Specimen Creek drainage in the northwestern corner of the park. These small headwater lakes have an andesite-basalt bedrock but show very low alkalinities (<200 µeq/l). The water supply of these lakes is primarily from snowmelt (YNP 1965-1981)) and lakewater chemistry appears to be influenced more by this dilute source than by reaction with the surrounding bedrock.

Field pH measurements were used to create a spatial pH map to complement alkalinity in determining geographical distributions of sensitivity (Figure 16). The pH map for Yellowstone shows most lakes with circumneutral pH's of 6.5-7.49, and most of the rest of the lakes slightly to strongly alkaline. Six of the 106 lakes have pH values less than 6.5. Of these six, two are unquestionably influenced by thermals and one probably so, and three are dystrophic lakes. As with the high alkalinity lakes, the greatest proportion of high pH lakes is found in the northern part of the park.

A similar map denoting sulfate concentrations for the Yellowstone lakes (Figure 17), shows a cluster of high sulfate lakes in the north and central east areas; these lakes are generally characterized by high alkalinity (>1600 µeq/l) and in some cases are found in low-lying marshy areas. Sulfate in these lakes probably has a biological and/or bedrock component (YNP 1965-1981). Sulfate concentration in lakes throughout the rest of the park shows no particular trends; most lakes show sulfate values <200 µeq/l, while a majority of lakes in the rhyolite bedrock have sulfate concentrations <100 µeq/l.

The alkalinity, pH, and sulfate maps for Yellowstone must be viewed with a number of factors in mind. First, all lakes for which "recent" (1965 or later) data were available were used to create the maps, regardless of ion balance. Some of the values, therefore, may be in question from a purely analytical view. Second, there exists a 16-year spread in chemical analyses for the maps: Lakes sampled once in 1965 are not distinguished from those sampled in 1980. In all cases, the most recent chemical measurements are used

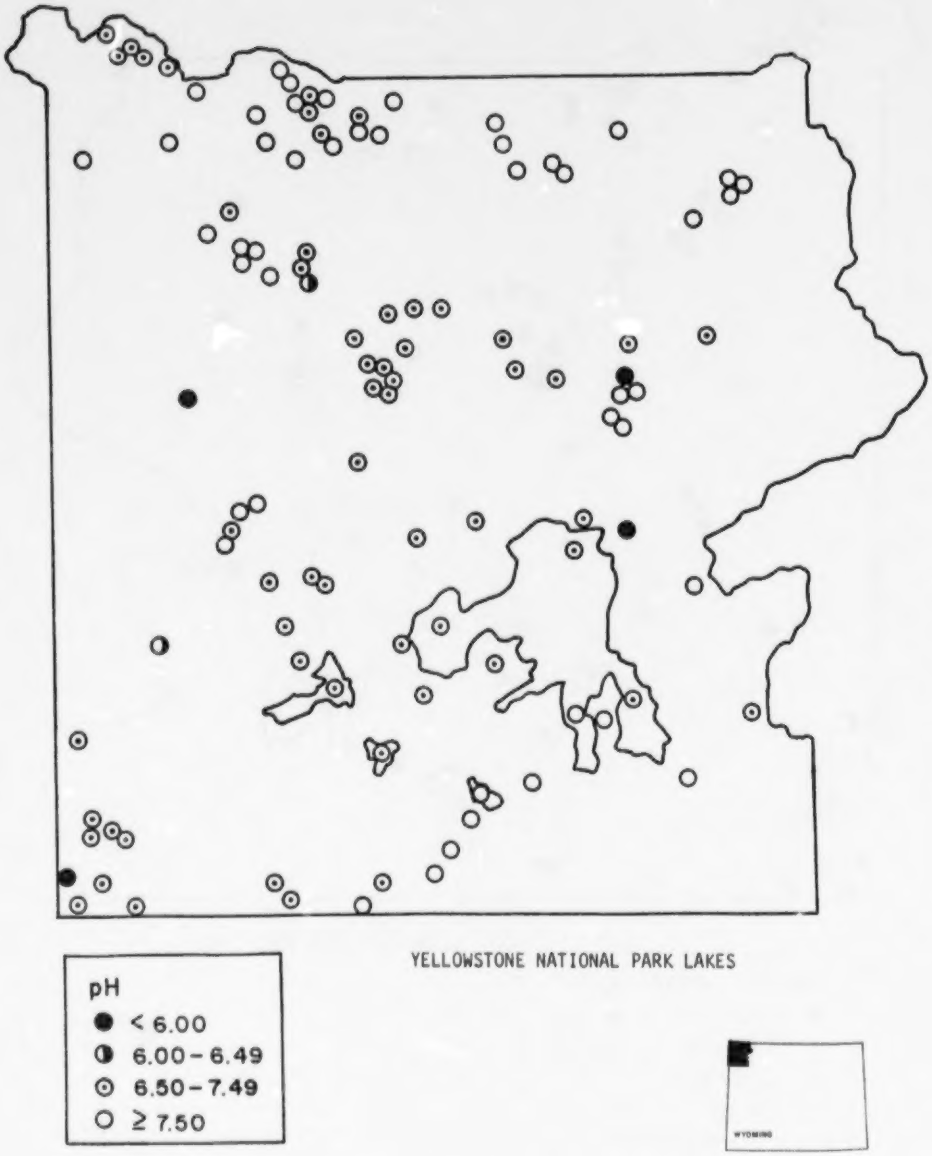

YELLOWSTONE NATIONAL PARK LAKES
pH
● < 6.00
◐ 6.00 - 6.49
⊙ 6.50 - 7.49
○ ≥ 7.50
WYOMING

Figure 16. pH map, Yellowstone National Park.

for each lake. Third, the water sources for the lakes vary, and reflect different residence times through different watersheds. Only two of the lakes with alkalinities <230 µeq/l have significant inlets, and most lack outflow. The primary source of water for these dilute lakes is groundwater and snowmelt (R. E. Gresswell, personal communication). A number of the less sensitive lakes have significant flow-through. Finally, humic lakes, geothermally

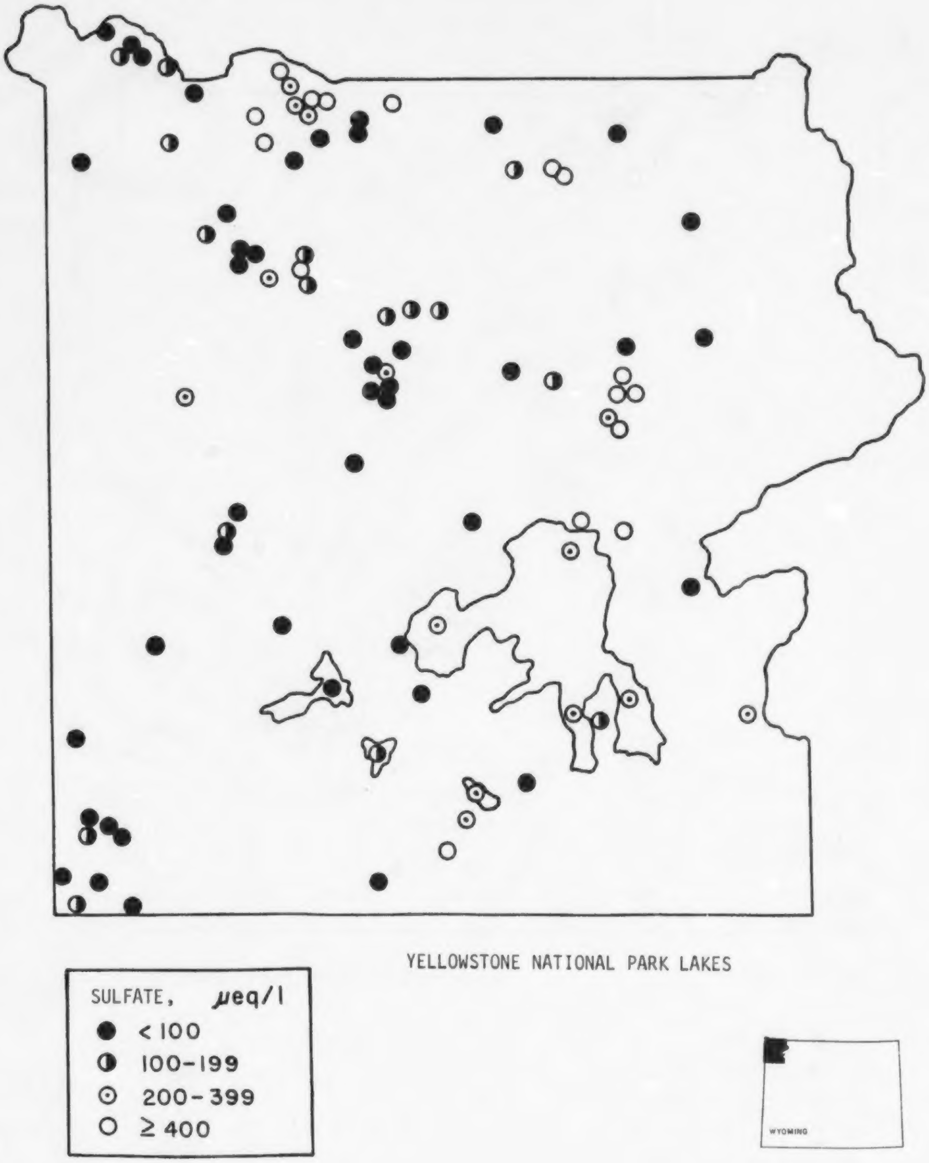

YELLOWSTONE NATIONAL PARK LAKES
SULFATE, μeq/l
● < 100
◑ 100-199
⊙ 200-399
○ ≥ 400
WYOMING

Figure 17. Sulfate map, Yellowstone National Park.

influenced lakes, and those fed by subterranean seeps through calcareous deposits are not distinguished from those lakes which more readily reflect the influence of the surficial geology. Indeed, many lakes in this geologically active area may be influenced by unknown factors. Figure 18 shows the location of the major thermal springs and geysers in the park (Waring 1965):

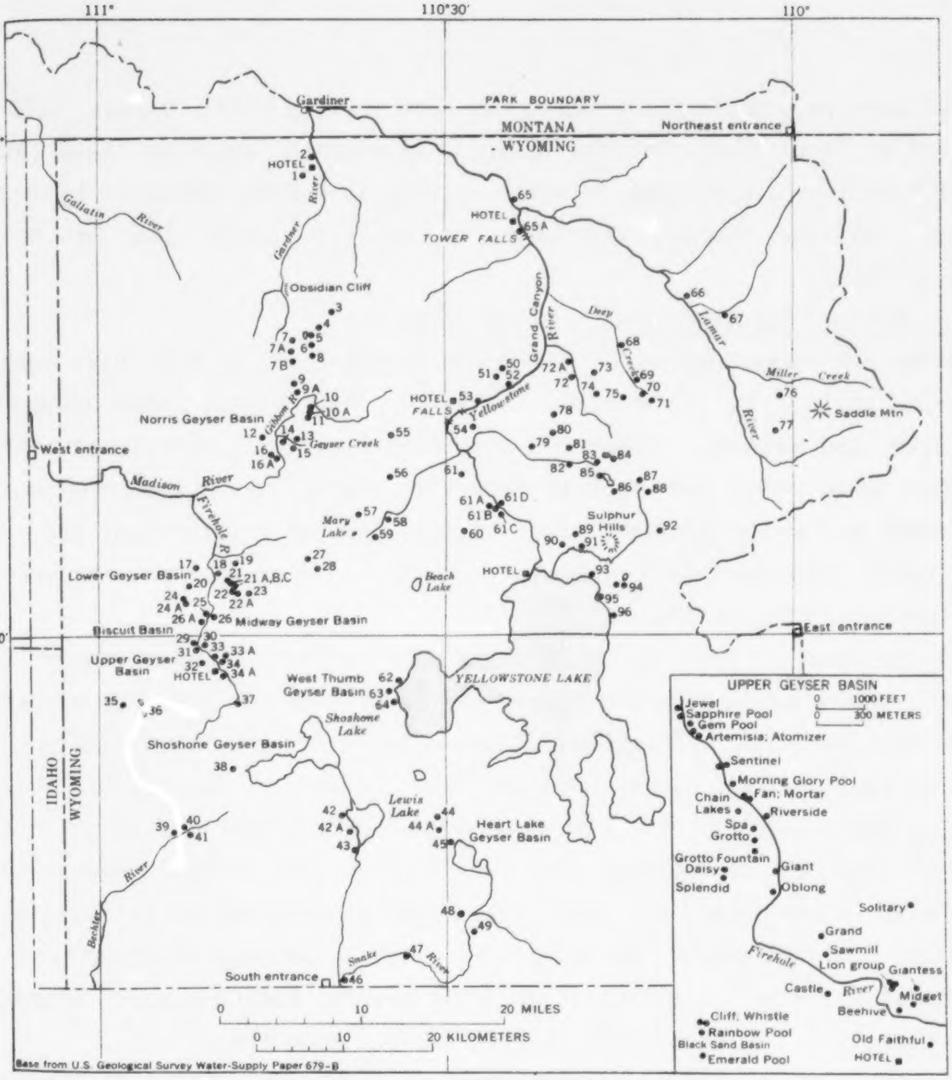


Figure 18. Location of hot springs and geysers, Yellowstone National Park (from Waring 1965).

springs and geysers in the park (Waring 1965): These are concentrated in geyser basins along the Firehole and Gibbon rivers, as well as north of Yellowstone Lake. Major hydrothermal activity in the park generally follows the southwest-northeast sweep of the rhyolite plateau.

Examination of alkalinity and pH data indicates that most of the lakes are well buffered against potential increases in rainfall acidity. One fourth of the surveyed Yellowstone lakes do report alkalinity values <230 µeq/l (defined as "sensitive" in this report), although a number of these (at least 7 of 30) receive significant internal acidity from humic acids or hydrothermal springs. All but four of the lakes in the < 230 µeq/l class are naturally barren of fish.

Factors Influencing Alkalinity (Sensitivity)

Numerous investigators (e.g., Galloway and Cowling 1978) have considered surficial geology as the critical factor in determining water chemistry of many lakes and streams. Commonly, surficial geology is correlated with water chemistry when soils are derived from the underlying bedrock, surface water originates as flow of incident precipitation through a watershed, and chemical constituents are derived primarily through ion exchange/mineral weathering reactions occurring in the soil.

As a whole, lakes in Yellowstone are influenced by far more complex factors. Three major glaciers caused the deposition of extensive allocthonous rubble in some areas. The chemical characteristics of this transported rock material may, in some cases, dominate lake chemistry. The ash and lava flows covering large areas of the park are dotted with hydrothermals which provide internal sources of sulfate and other chemicals. Underground springs, especially in the north, may contribute large concentrations of dissolved ions to lakes in "unreactive" bedrocks. Finally, watersheds frequently show the effects of a number of different geologic events, making simple separation of most lakes into "dominant" bedrock type subject to error.

Considering only lakes with good ion balances and no known humic or thermal influence, a separate variance t-test was used to determine if significant differences existed in surface water chemistry between the volcanic and the mixed-geology regions. The results of the pairwise comparison indicate that the alkalinity and the base cation sum are significantly different between the volcanic (FR, RP) and the older sedimentary-volcanic (GT, AB, BT) regions of the park, with $p < 0.01$ (Table 19). Both alkalinity and base cations are significantly lower in the volcanic regions. There appears to be no statistically significant difference in lake sulfate concentration between the two regions, indicating that local sulfur sources are not confined to a single region, but may influence lakes in many areas of the park.

The statistical results indicate that, with the best available separation of "poor" data (bad ionic balance, thermal or humic influence), lakes in the

Table 19. Regional alkalinity of Yellowstone National Park lakes.

Region	Mean alkalinity (µeq/l)	No. of samples	Range (µeq/l)
RP[a]	182	8	80-360
FR	320	2	320
GT	1468	8	640-2280
AB	1493	3	240-3520
BT	1907	3	160-4800

[a] FR = Ralls River hydrologic unit, RP = Rhyolite Plateau hydrologic unit, GT = Gallatin hydrologic unit, AB = Absaroka hydrologic unit, BT = Beartooth hydrologic unit.

Rhyolite Plateau and Fall River basalt region (i.e., those most influenced by volcanic bedrock) are potentially more sensitive to acidification than those in the non-volcanic northern and eastern ranges. The term "sensitive" is, as always, relative, for the more sensitive lakes in Yellowstone show similar geology to the least sensitive lakes in Rocky Mountain National Park (this study).

Alkalinity is commonly observed to decrease with increasing elevation, as soil depth and development, and watershed residence time are decreased. A fairly strong alkalinity-elevation correlation exists for a number of watersheds in Rocky Mountain National Park, with only a weak trend for the volcanic-andesite dominated Upper Colorado watershed (Figure 8). Results for the Yellowstone lakes dominated by rhyolitic bedrock are intermediate (Figure 19), showing a fairly strong correlation, except for two lakes located in deep depressions at the edge of the formation. The Yellowstone rhyolite is a somewhat more homogeneous bedrock than the Upper Colorado geology; this may explain the clearer gradient.

An evaluation of the relationship of sensitivity to basin characteristics was attempted by statistical analysis of water quality data of lakes from differing hydrologic regions. Lakes in regions dominated by volcanic bedrocks

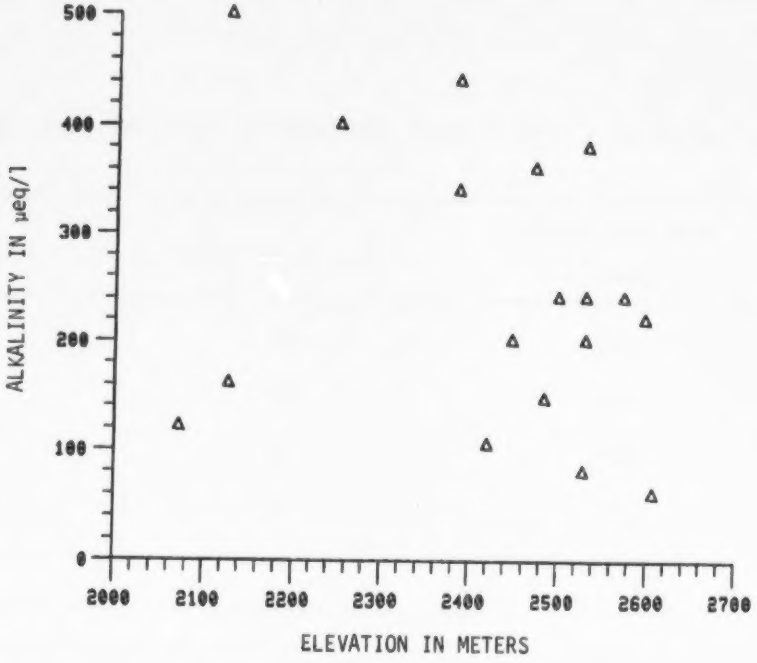


Figure 19. Alkalinity versus elevation, lakes draining rhyolite bedrock, Yellowstone National Park.

show the lowest alkalinities and base cation concentrations. On the whole, these lakes may be considered the most sensitive in the park to acidification. A wide spread in chemistry values for the other lakes indicates that deep springs or local geologic deposits may greatly influence water chemistry.

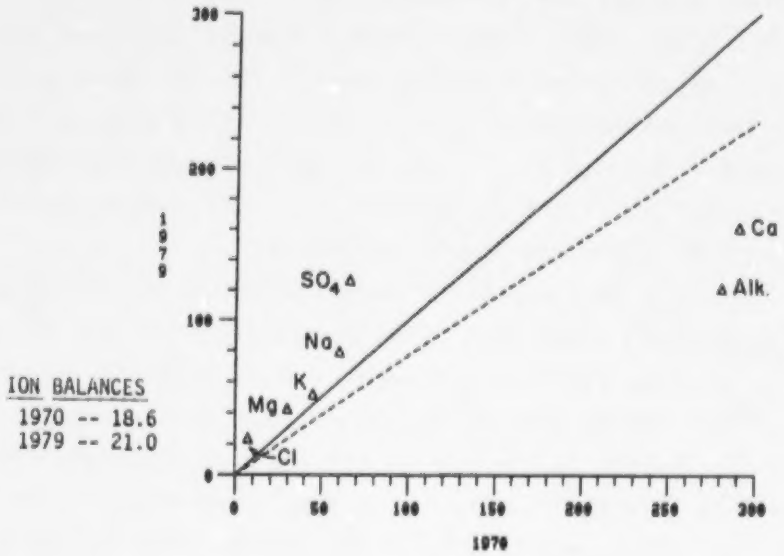
Historical Changes in Surface Water Chemistry

Acidification trends may be determined in two major ways: Analysis of historical data, and use of (empirical or mechanistic) predictive models. The major difficulties with historical data are that (1) water chemistry may change daily and seasonally in relation to biological activity, (2) methodology may change over the years, and (3) hydrological and meteorological conditions may not be comparable. Minimization of daily and seasonal fluctuations is best accomplished by holding these parameters as constant as possible, and by comparing mean values of a number of lakes. All water chemistry data used in this study are from the summer months of June through September, but daily fluctuations in the chemistry were not determined, since lakes were sampled at different times of the day from one year to the next. Changes in methodology may be accounted for by application of "correction factors" if earlier methods are systematically biased (e.g., Burns et al. 1981; Pfeiffer and Festa 1980). When complete chemical analyses are available, ion balances may serve as a quality check. For the Yellowstone data, all alkalinities were determined using colorimetric titrations, and all pH's with either the Hach or Hellige kit. Since a single lab performed analyses of Yellowstone Park water since 1974 and methods have not changed considerably, data collected since that year are highly comparable.

The final difficulty with historical data is related to differing hydrological and meteorological conditions. Ionic concentrations may be substantially reduced by dilution during a wet period and increased by concentration during a dry period. While absolute concentrations have changed, relative concentrations (with respect to the sum of all ionic constituents) have not. Figures 20 through 23 attempt to account for simple hydrologic variations in comparing historical with recent data. The dotted line in each figure connects the origin with the ion sum for each year. The position of each individual ion with respect to that line indicates whether its relative concentration has increased (above the line) decreased (below the line) or remained constant over the period of time indicated (from Henriksen 1982). In Figures 20 through 23, a solid 45 degree line is included for comparison. By indicating relative changes in surface water concentration, the plots reduce interpretive error due to differences in hydrologic conditions. Figures 20 through 23 represent available historical data for lakes with alkalinity values of <500 µeq/l, including those with poor ion balances (i.e., >20% variations).

Of the seven lakes shown in the historical comparison plots, three show a relative decrease in alkalinity (High, Crescent, Grebe) and increase in sulfate over the 10-year period, two show the reverse trend (Wolf, Ice), and two show no change in alkalinity (Crag, Cascade). Thus, the overall trend for the seven lakes appears random. Two of the lakes showing alkalinity declines are located in the extreme northwestern corner of the park in a group of five small snowmelt-seepage lakes in the Specimen Creek watershed. These lakes show uniformly low alkalinities; however, ion balances are poor. More sampling would be necessary to make definitive statements about the sensitivity of these lakes. Of the three lakes which show an increase in lake sulfate, the relative sulfate concentration changes (averaging 80 µeq/l) are

CHEMICAL COMPOSITION -- 1970/1979
HIGH LAKE
YELLOWSTONE NATIONAL PARK



CHEMICAL COMPOSITION -- 1970/1979
CRESCENT LAKE
YELLOWSTONE NATIONAL PARK

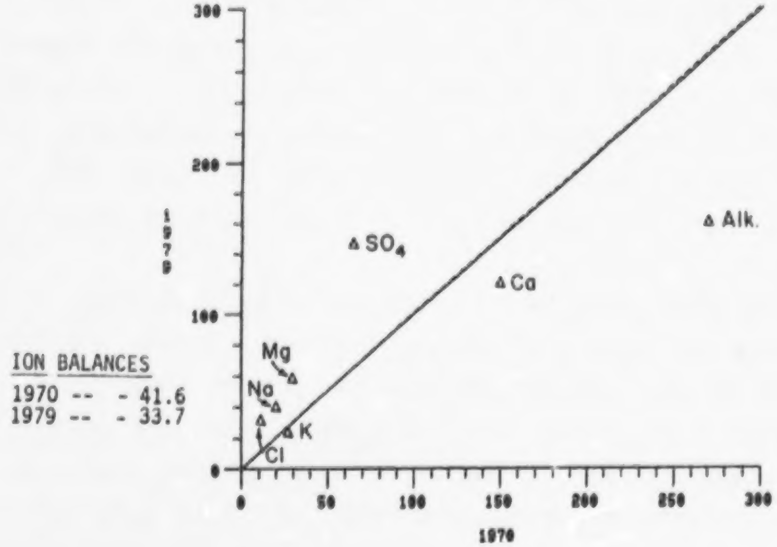


Figure 20. Historical chemistry comparisons, High and Crescent Lakes. All concentrations in μeq/l.

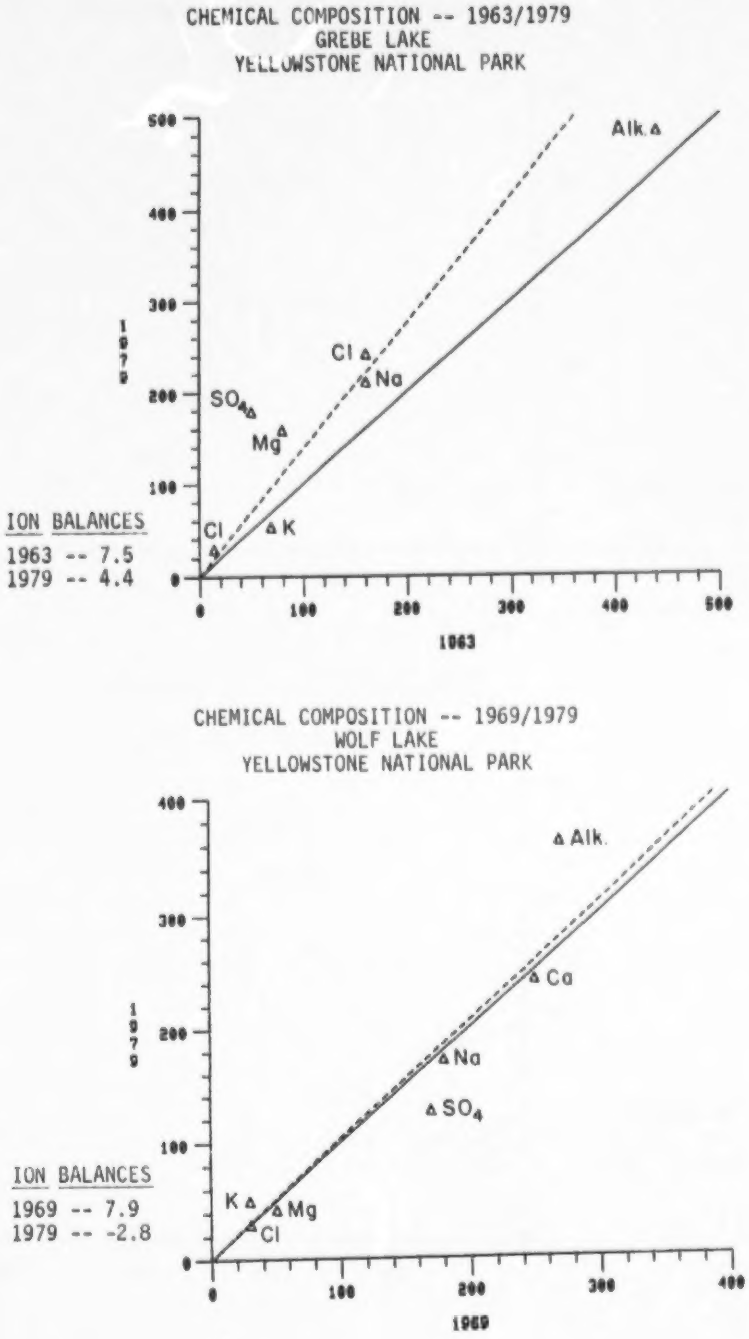
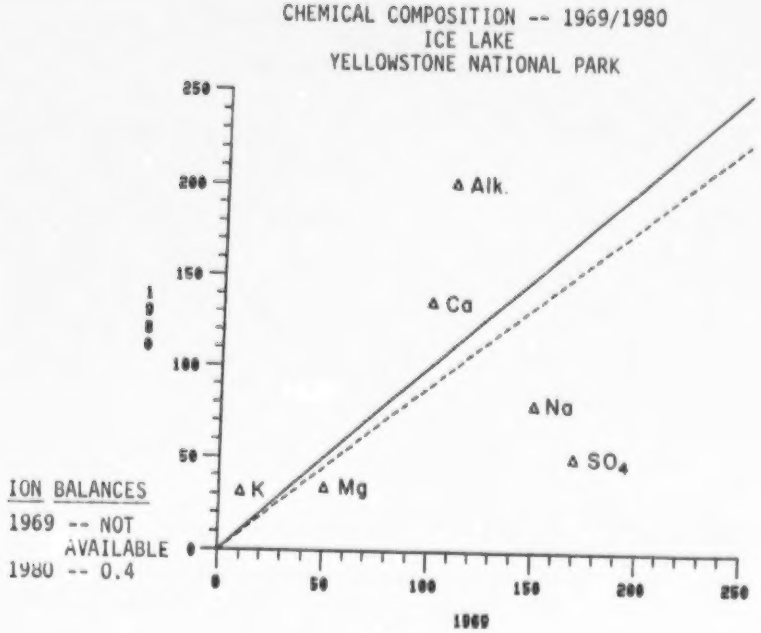


Figure 21. Historical chemistry comparisons, Grebe and Wolf Lakes. All concentrations in µeq/l.



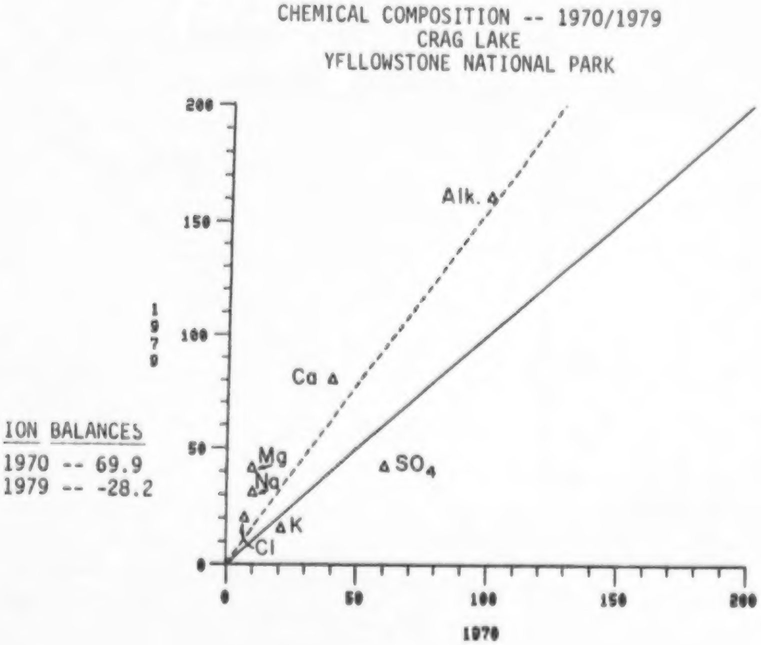


Figure 22. Historical chemistry comparisons, Ice and Crag Lakes. All concentrations in μeq/l.

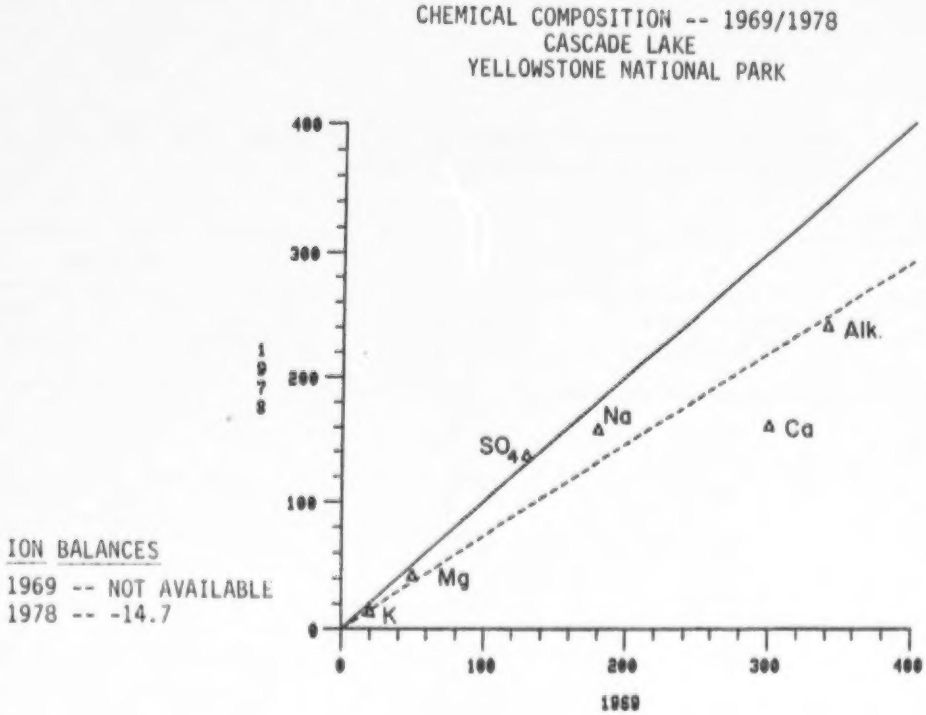


Figure 23. Historical chemistry comparisons, Cascade Lake. All concentrations in µeq/l.

considerably greater than the sulfate load in precipitation (approximately 33 µeq/l). These sulfate changes are probably too great to be caused by acid precipitation and likely reflect the influence of local natural sources of sulfate.

The relative concentrations of sulfate and alkalinity were also computed for the seven lakes and are shown in Table 20. Comparing data in terms of relative concentrations, or percent of each ion in relation to the total ion sum, is another method to minimize the influence of sampling under different hydrologic conditions. t-tests on historical versus recent relative concentrations of alkalinity and sulfate for the seven lakes show no significant changes in these parameters over time.

Predictive models, such as that developed by Henriksen (1979), generally assume that bicarbonate lost in water acidified by atmospheric deposition is stoichiometrically replaced by sulfate, as strong acids from anthropogenic

Table 20. Relative concentration[a] of alkalinity and sulfate, lakes with historical data.

Lake	Alkalinity		Sulfate	
	Historical (1963-70)	Recent (1978-80)	Historical (1963-70)	Recent (1978-80)
Crescent	47.2	27.8	11.3	25.2
High	36.1	20.1	8.4	20.9
Cascade	33.3	30.0	12.7	16.9
Ice	18.6	36.2	28.8	9.1
Crag	40.2	41.2	24.4	10.7
Wolf	27.5	35.6	17.3	12.3
Grebe	45.3	35.8	5.1	13.2
$\bar{x}$	35.5	32.4	15.4	15.5

[a] Relative concentration = [ion of interest]/ion sum × 100.

sources titrate existing alkalinity or replace bicarbonate as a major weathering ion. This assumption implies a negligible increase in base cation release from soils with acidification. A second assumption is that "internal" natural sources of sulfate are negligible. However, Figures 20 through 23 indicate that historical changes in alkalinity are generally balanced by changes in both calcium (cation compensation for acidity increases) and sulfate, in violation of the first assumption. The second assumption is also invalid for Yellowstone, which is heavily influenced by numerous geothermal sources of sulfur. This may be illustrated by comparing the concentrations of chloride and sulfate among the Yellowstone lakes: chloride (Figure 24), assumed to be a conservative ion, remains relatively constant in nearly all the Park lakes. In this plot, four of the five outliers represent large, old lakes (three samples from Yellowstone Lake and one from Lewis Lake); these are probably influenced by long-term concentration by evaporation. In contrast, sulfate

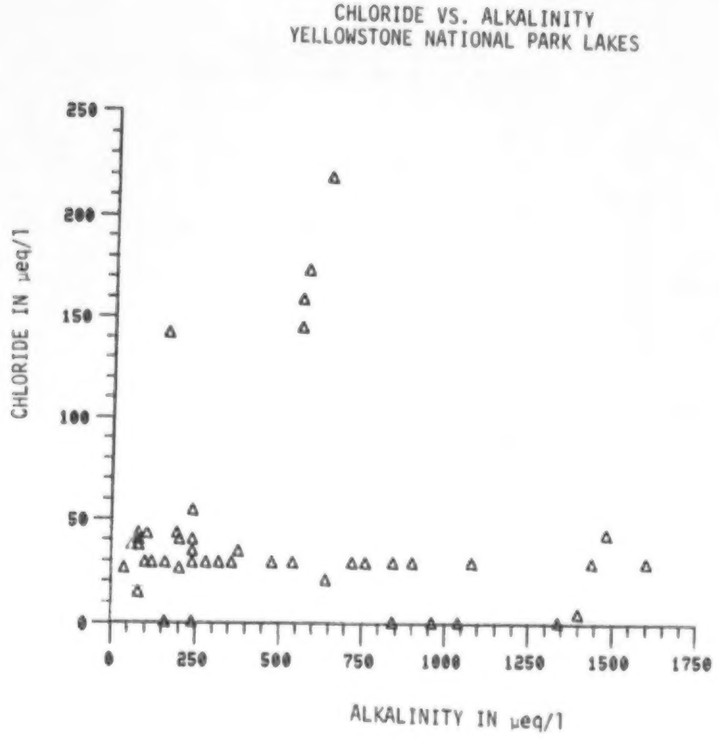


Figure 24. Chloride versus alkalinity, Yellowstone National Park lakes.

concentration throughout the Park lakes is highly variable (Figure 25). In Figure 25, a cluster of 17 low sulfate, low alkalinity lakes (mean sulfate concentration = 35.8 μeq/l) is evident in the Park, along with a wide scattering of higher sulfate lakes. Thus, the unique characteristics of Yellowstone make use of a Henriksen-like predictive acidification model inappropriate.

Detecting historical changes in surface water chemistry for Yellowstone is confounded by natural variability in water chemistry, internal sources of acidity, and a scarcity of reliable historical data. Yellowstone precipitation is currently not highly acid, nor do the lakes appear acidified by anthropogenic activity. No significant overall change in water chemistry was noted from lakes sampled once, then resampled several years later. The dilute lakes in the rhyolite plateau and also in the far northwestern corner of the Park may be the most subject to future acidification.

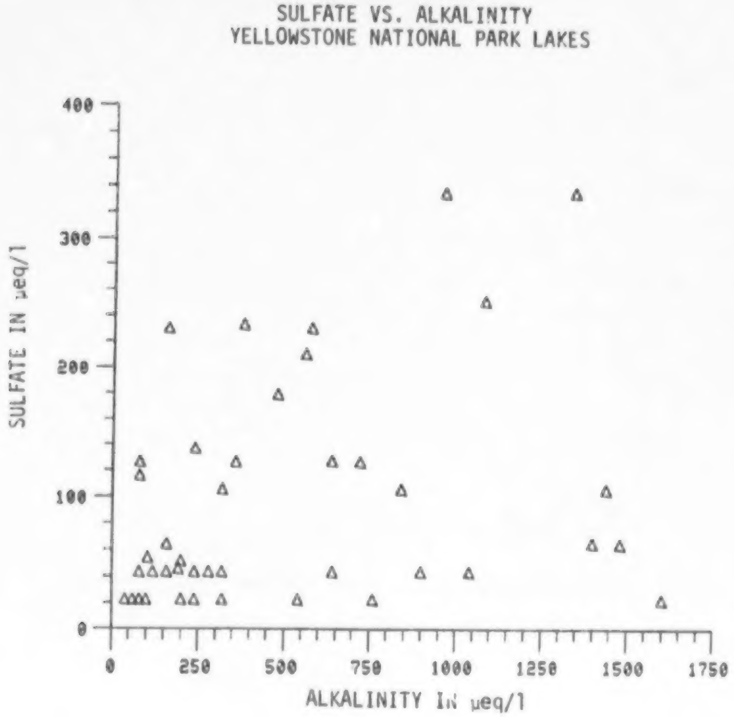


Figure 25. Sulfate versus alkalinity, Yellowstone National Park lakes.

Current Status and Future Trends in Surface Water Chemistry

Current, historical, and future acidification scenarios depend upon changing composition of precipitation. Yellowstone receives an average of 42 cm of rainfall annually (NOAA 1970), but, because of the Park's great size and varied terrain, precipitation distribution is not homogeneous. The Continental Divide intercepts eastward moving storms from the Pacific, causing the greatest amount of precipitation near the Divide in the southwest, and the lowest in the low altitudes. Up to 1.2 m of snow may accumulate in the Park on average winters. Figure 26 indicates how weekly averaged pH and sulfate concentrations over the NADP deposition-monitoring site vary with season from June 1980 to January 1982. Although no overall trends are evident, chemistry is quite variable, with a few sharp sulfate peaks over the year. These high peaks represent the lowest volume periods of the record, and are not correlated with especially low pH.

In 1981, weighted average precipitation pH at the NADP collecting station was 5.2 and weighted average annual sulfate concentration was 33.5 µeq/l.

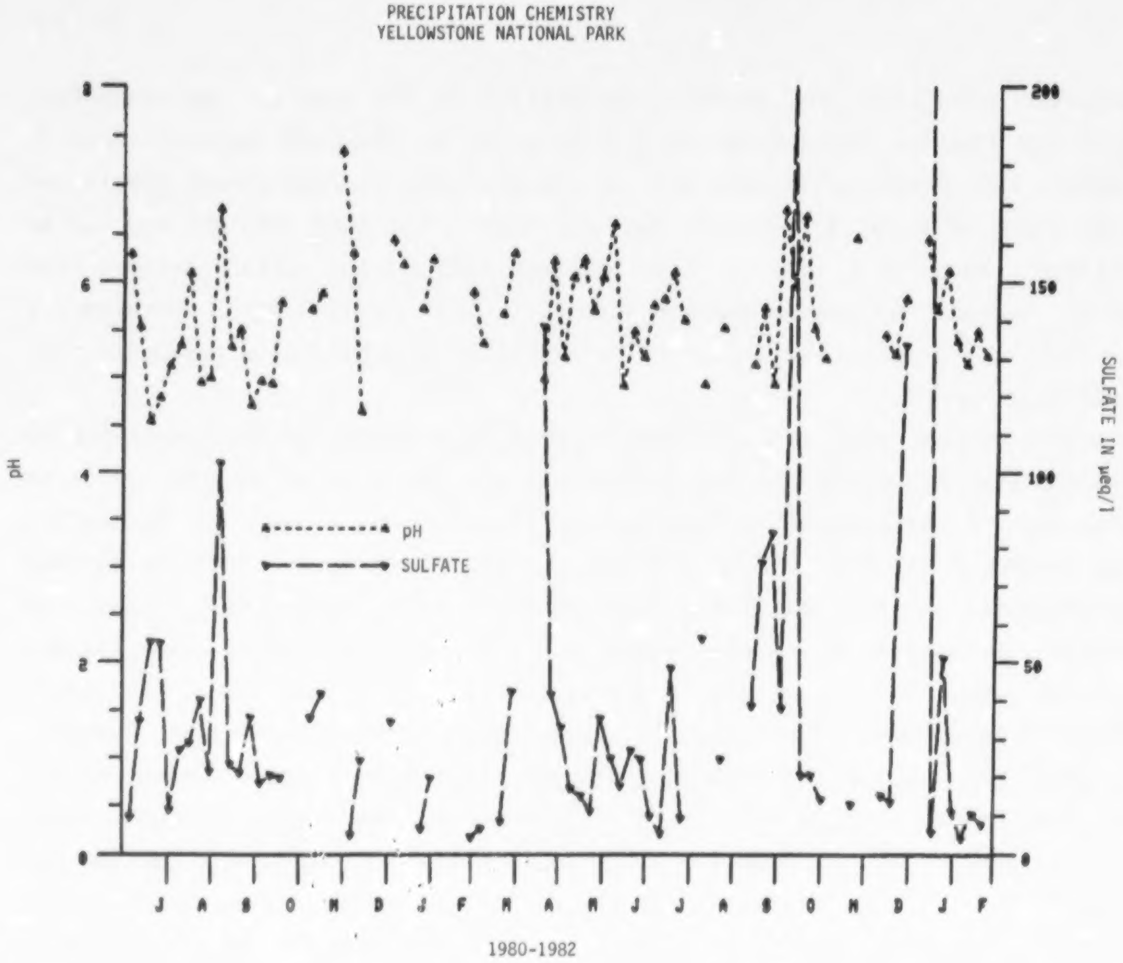


Figure 26. Precipitation pH and sulfate concentration, Yellowstone National Park, WY, 1980-1981 (from NADP 1981).

During the same year, over a "typically" acidified area of the eastern U.S., Hubbard Brook, New Hampshire, precipitation pH averaged 4.4 and precipitation sulfate averaged 48.9 µeq/l. A comparison of these two sites indicates that the northwestern Wyoming area is currently not threatened by highly acid precipitation.

The major anionic contributor to strong acidity is the sulfate ion. Although sulfate mobility can be affected by soil adsorption and biological uptake (Johnson and Cole 1980), inputs and outputs of this ion have been found approximately equal in a number of lakes, such as those in the Canadian Shield region (NRCC 1981). Long-term increases in sulfate deposition to sensitive lakes in Yellowstone could result in increased sulfur concentration and potential acidification. As discussed previously, the mean sulfate concentration for the low sulfate-low alkalinity group of lakes was approximately 36 μeq/l. This value corresponds well to the estimated average annual precipitation input of about 33 μeq/l as derived from recent NADP data and may, as an extreme, represent a 100% contribution from rainfall (no sulfate derived from soils, bedrock, or nearby thermal sources). This simplification represents a maximum, and ignores any potential soil sulfate adsorption and residence time considerations.

Yellowstone does not currently receive acid precipitation comparable to the eastern United States. The low sulfate concentration of 36 μeq/l falls in the range of "background" sulfate for the Canadian Shield lakes (30-60 μeq/l), and probably is also almost entirely of natural origin. This is further corroborated by the relatively high rainfall pH. In contrast, lakes and streams in acidified regions throughout the U.S. and Canada show average sulfate ranges of 3 to 4 times that (Table 21). The higher values of sulfate found in some Yellowstone lakes is assumed due to groundwater, soil, bedrock, or geothermal sources. Yellowstone probably experiences little current acidification from acid precipitation. Considering the highly variable lake sulfate concentrations, however, local sulfate sources undoubtedly pervade the park. Given the existence of geothermal, local atmospheric, bedrock, and underground spring sources of sulfate, it is impossible to state how anthropogenic acidification will affect these lakes.

Table 21. Sulfate levels in selected acidified waters.

Area	Sulfate range (μeq/l)	Reference
Southern Ontario (lakes)	160-220	Dillon et al. (1978)
Nova Scotia (lakes)	100-140	NRCC (1981)
New Hampshire (streams)	129-142	Likens et al. (1977)

It is possible, however, to approximate how Yellowstone would be affected if rainfall over the park were to change composition to approximate the acidity of typically eastern precipitation. The monitoring station at Hubbard

Brook experimental forest provides the longest continuous record of precipitation chemistry in the United States. Over the ten year period from 1963 to 1974, the weighted annual mean concentration of sulfate in precipitation was 60.3 μeq/l, and for nitrate, 23.7 μeq/l. A far shorter record (1.5 years) is available for the evaluation of precipitation chemistry of Yellowstone National Park, however, a value of approximately 30 μeq/l sulfate and 10 μeq/l nitrate is reasonable (NADP 1981). Thus, a doubling of the sulfate and nitrate concentration of Yellowstone precipitation from approximately 40 to 80 μeq/l would roughly yield the mean precipitation chemistry for these constituents in the east. Two extremes exist in the response of watersheds to this chemical change. As a minimum, all of this new sulfate and nitrate would be incorporated into the watershed, i.e., adsorbed onto soil particles or tied in biotic cycling. As a maximum, all of the new strong acid-derived anions would be introduced into the lake ecosystem. Thus, the range of acidification of Yellowstone lakes would be from 0-40 μeq/l. The maximum loss of alkalinity expected, under these conditions, is 40 μeq/l; the true loss is probably somewhat less. A loss of 40 μeq/l alkalinity from each lake in Yellowstone would shift the number of "sensitive" (alkalinity <230 μeq/l; no significant hot springs) lakes from 24 to 33. Only one of these new lakes has a significant trout population, the rest are historically barren.

FISH POPULATIONS

INTRODUCTION

The loss of fish populations in acidified lakes and streams has been the most publicized effect of acidic deposition. Although it is believed that other aquatic biota are also unfavorably affected by increasing acidity, effects on fish have been the most widely studied and documented. The basis for the RMAS was to determine if, in fact, there was any evidence that the acidification of waters in the most sensitive areas of the Rocky Mountain region had progressed to a point that might endanger any of the fish species. The evaluation relied on the acidity and alkalinity data from RMNP and YNP and published and unpublished fisheries information for the Rocky Mountain region.

Assessment Approach

Assessment of the potential responses of fish populations in the Rocky Mountain region to acidification, resulting from increased atmospheric strong acid deposition, was approached in the following manner:

1. Areas potentially sensitive to acidification were defined on the basis of relationships between water quality, geology, and soils, developed in representative watersheds in RMNP and YNP.
2. Information on predominant fish species, fisheries, and management policies prevailing in potentially sensitive areas were obtained from the published literature and unpublished fishery survey data.
3. The possible effects of acidification on the species at risk were evaluated from published information on life history patterns, in relation to expected changes in water quality. Potentially critical life history stages were identified on the basis of documented effects on species with comparable life histories and habitat requirements, in regions where acidification has already occurred.
4. The implications of possible acidification effects on fish populations for State and Federal management policies were considered, critical information gaps were identified, and future research direction recommended.

Evaluations in this study of water chemistry data obtained from RMNP and YNP and data from other studies in the Rocky Mountains have not revealed any instances of chronic acidification at levels that would be detrimental to fish survival. Chronic acidification of surface water occurs where rates of base supply, derived from weathering processes in the drainage basins, are exceeded by rates of strong acid input from atmospheric depositions. Such conditions have been observed in sensitive areas of eastern North America and Scandinavia (Wright et al. 1980), where chronically acidified lakes and streams exhibit an absence of bicarbonate buffering, low pH (<5.0), and increased levels of potentially toxic metals. Fish populations are generally absent or extremely stressed at these chronic levels of acidification (Schofield 1976; Muniz and Leivestad 1980). However, it is important to recognize that perturbations leading to the observed decimation of fish populations in these chronically acidified waters probably were initiated at much earlier, transitional stages of acidification, prior to the complete loss of bicarbonate buffering in the systems (Henriksen 1980; Schofield 1982).

As indicated in the previous sections on water chemistry and geology, a large number of headwater drainages in the geologically sensitive areas of the Rocky Mountains exhibit extremely low rates of base supply, as indicated by the low alkalinity and cation levels. These drainage systems border on a transitional stage of acidification, at current levels of atmospheric strong acid deposition. Even minor excursions of increased strong acid loading, as might occur during the early stages of snow-melt, could episodically acidify these systems. The presently available water chemistry data represent late snow-melt or baseflow conditions, hence the contemporary occurrence of such events is unknown. The probable consequences of such perturbations for indigenous fish populations, should they occur in these sensitive drainage systems, are considered in subsequent discussions of fish responses to water quality change.

RESULTS AND DISCUSSION

Fish Resources in Potentially Sensitive Areas of the Rocky Mountains

The general areas in the Rocky Mountains potentially sensitive to acidification are situated in the alpine (>3,200 m) and upper montane (2,500-3,200 m) altitudinal zones. Sensitivity of specific drainage basins is tempered by local variations in bedrock and surficial geology, as discussed previously. Fish species richness and standing crops are relatively low in these headwater drainages and many were originally devoid of native fish populations, because of natural barriers to colonization in the form of falls and stream gradients impassible to fish. However, most of the originally barren headwater lakes were subsequently stocked with either native or exotic salmonids, beginning in the early 1880s (Pennak 1963). The cutthroat trout (*Salmo clarki*) is the only native trout in the area and it is represented by several subspecies restricted to specific drainage systems. The only other native species locally present in these sensitive watersheds are the grayling (*Thymallus signifer*), several species of the mountain sucker (*Pantosteus* spp.), sculpin (*Cottus* spp.), and the mountain whitefish (*Prosopium williamsoni*). Introduced, non-native species that have become regionally established include the brook trout (*Salvelinus fontinalis*), rainbow trout (*Salmo gairdneri*), and brown trout (*Salmo trutta*). The intentional and inadvertent introduction of these species, particularly the brook trout and rainbow trout, has been most detrimental to the native cutthroat trout stocks, both because of competitive exclusion and hybridization. Additionally, indiscriminate hatchery plantings of cutthroat have so blurred the genetic integrity of this species, that only in a few high lakes and streams can the original subspecies still be distinguished morphologically (Pennak 1963). The problems associated with the preservation and maintenance of these subspecies will be discussed further in the section on wild trout management, with specific reference to the watersheds in RMNP.

The extensive fisheries data base for YNP provides both a detailed chronology of the changes in fish distribution and management policies for this region since the 1800s. The comprehensive summary of fish stocking activities in YNP by Varley (1981) provides the most recent, detailed information on the status of fish populations in the Park. An earlier publication by Fromm (1941) provides a more anecdotal account of the early hstory of fish surveys. Although eighteen species of fish (12 native species) are currently recorded as being present in YNP waters, their distribution is quite limited. Many of the lakes and streams in YNP were and still are fishless, primarily because of the physical limitations to colonization described earlier. Lakes and streams in approximately 40% of YNP (Figure 27) were estimated to be devoid of fish in

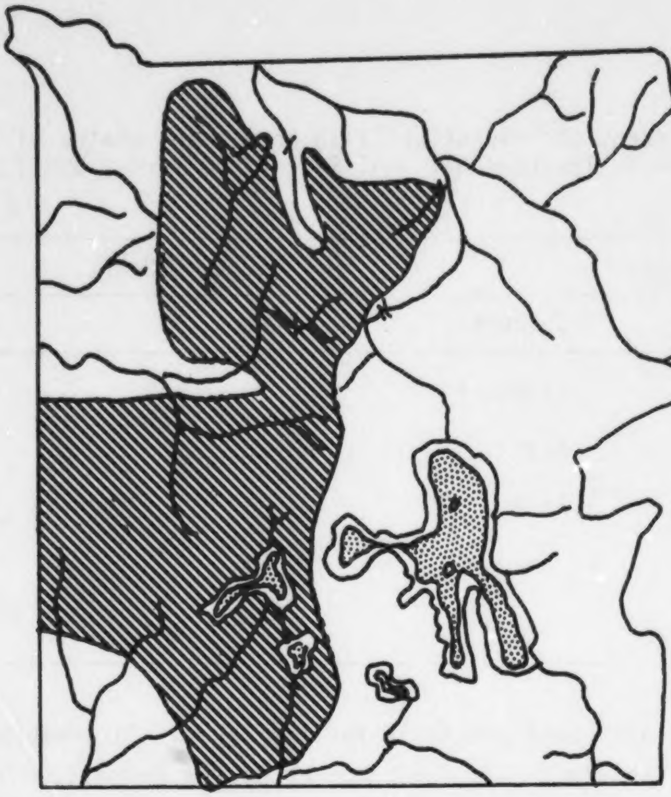


Figure 27. Cross-hatching shows the area in Yellowstone National Park found barren of fishes by Jordan in 1889, with the exception of sculpins in the Gibbon River above Gibbon Falls (from Fromm 1941).

the 1800's (Jordan 1889). Early fishery management efforts sought to establish fishes in these barren waters through extensive plantings of both native and exotic species. Varley (1981) provides a detailed chronology of these stocking efforts. Many of the previously fishless headwater streams and lakes received introductory stockings during the period 1920-1935. Although fish populations were probably established temporarily in most of these waters by stocking the majority of the initially fishless lakes are presently barren once again. However, this is not the case for streams. Most of these historically fishless streams are currently supporting viable fish populations (Table 22). The difference probably reflects the lack of suitable spawning habitat in many of the small headwater lakes. In the previous section 23 potentially sensitive lakes were identified in YNP (alkalinity <200 µeq/l)

Table 22. Current and historical fish population status of lakes and streams in Yellowstone National Park (from Varley 1981).

Category		Number	
Historical	Current	Lakes	Streams
Fishless	Fishless	29	2
Fishless	Fish	18	38
Fish	Fish	11	17
Unknown		13	16
Total		70	73

from the water chemistry data available for 107 lakes. Information on historical and current fish status obtained for 11 of the sensitive lakes is summarized in Table 23. Only one of the lakes supported cutthroat trout historically and the only other species currently present is the introduced brook trout in three of these lakes.

Fisheries Management Policies in Potentially Sensitive Areas

State and federal policies which must be considered in assessing potential acidification impacts on fish populations include state level wild trout management policies, National Park Service aquatic resource management policy, and U.S. Fish and Wildlife Service implementation of the Endangered Species Act, including cooperative agency efforts.

The NPS policies governing the management of aquatic ecosystems in designated Natural Zones are particularly relevant to the sensitive areas identified in RMNP and YNP. The primary goal of resource management programs in natural zones is the preservation and restoration of native aquatic ecosystems, including those waters originally barren of fish. Park waters falling into this category are allowed (or in some cases "rehabilitated") to revert to their original fishless condition. This would include the majority of sensitive waters in YNP and a large number in RMNP as well. Strict interpretation and adherence to this policy would seem to make the question of

Table 23. Total alkalinity and fish population status for sensitive lakes in Yellowstone National Park (from this study, and Varley 1981).

Lake name	Alkalinity (μeq/l)	Fish Status Historical	Fish Status Current
Wrangler	40	Fishless	Fishless
Summit	60	Fishless	Fishless
Shelf	80	Fishless	Fishless
Mt. Everts	160	Fishless	Fishless
Ice	200	Fishless	Fishless
Ranger	160	Fishless	a
Obsidian	80	Fishless	brook trout
High	170	Fishless	cutthroat
Forest	192	Fishless	cutthroat[a]
Trilobite	200	Fishless	brook trout
Robinson	100	cutthroat	brook trout[a]

[a] Status questionable

potential acidification one of largely academic concern, with little relevance for fisheries programs. However, there are two important exceptions to this policy which should prioritize concern for the potential acidification of these waters. In some previously fishless waters, populations of either native or non-native fishes have become well established. If these established populations represent distinctive sub-species (particularly of endangered or threatened indigenous species) or valuable genotypes of non-native species, the populations may be designated as "naturalized" and managed as integral components of the ecosystem. Similarly, should research indicate the need to stock or re-locate threatened or endangered species, fishless or formerly fishless waters may be utilized as refugia for these species (Watson 1980; Jones 1980).

The relatively recent evolution and implementation of "Wild trout management" programs (most notably, the Colorado Division of Wildlife Commission's Wild Trout Policy, adopted in 1982) in the Rocky Mountain states is indicative of the widespread concern for the depletion of wild trout stocks. The objectives of these programs are diverse and although they are user oriented, they share a common objective with NPS and FWS programs for the protection of native species. Cooperative efforts are particularly evident and vital in programs developed for the protection and restoration of endangered or threatened species (Johnson and Rinne 1982; Behnke and Zorn 1976). Genetic swamping, habitat destruction, and competition with introduced species are primary reasons for the widespread demise of native trout in the Rocky Mountain Area (Behnke 1979). The Endangered Species Act provides a vehicle for the restoration of these western salmonids and recovery action programs are currently in place throughout the region. Implementation of these programs first requires listing of the species as endangered or threatened, which involves extensive study and documentation (Johnson and Rinne 1982). In addition to affording the listed species protection, under the conditions of the Act, habitats necessary for their survival are also afforded protection from adverse alteration or destruction. How this condition might apply to federal programs that influence the potential for acidification of these habitats is unclear at this time. The general components of recovery plans entail definition of the genetic purity of the population(s), survey and monitoring of existing populations, evaluation of habitat in existing and candidate reintroduction waters, and reestablishment of the native populations.

Endangered or threatened Salmo species present in potentially acid sensitive regions of the Rocky Mountains include several subspecies of the cutthroat trout. These fish and their listings are given in Table 24. The life history patterns of these species and the potential problems that acidification might impose on restoration programs in sensitive watersheds are considered in the following section.

Table 24. Endangered and threatened *Salmo* genotypes in the Rocky Mountain Region.

Common name	Scientific name	States	Listing status
Greenback cutthroat[a]	*Salmo clarki stomias*	Colorado	Endangered
Colorado cutthroat	*Salmo clarki pleuriticus*	Colorado, Wyoming	Threatened
Westslope cutthroat	*Salmo clarki* subsp.	Montana	Endangered
Eastslope cutthroat	*Salmo clarki* subsp.	Montana	Endangered
Snake River cutthroat	*Salmo clarki* subsp.	Wyoming	Rare
Rio Grande cutthroat	*Salmo clarki virginalis*	Colorado, New Mexico	Endangered
Gila trout[a]	*Salmo gilae*	New Mexico	Endangered
Arizona trout[a]	*Salmo apache*	Arizona	Threatened

[a] Indicates nationally recognized as endangered.

Potential Impacts of Acidification on Fish Populations

The few remaining native trout populations in interior regions of the Rocky Mountains persist only in small, isolated headwater drainages. These native cutthroat populations prefer and function best at lower temperatures than other species. With few exceptions, the cutthroat coexist and dominate introduced species only in these cold, headwater situations (Behnke 1979). Unfortunately, the displacement of these rare and endangered genotypes to headwater drainages also makes them most susceptible to potential acidification in these sensitive habitats. Because of the current endangered status of these fish, the *Salmo clarki* complex must be considered the primary species at risk and priority is given here to a consideration of potential acidification impacts on these populations.

Given the restricted distributions of the subspecific cutthroat populations and the geologic heterogeneity in watershed sensitivities to acidification in the Rocky Mountains, current juxtaposition of specific populations significantly determines their relative sensitivity to any regional increase in acidic deposition. The risk of possible extinction, resulting from acidification, could certainly be lessened if management recovery teams had prior knowledge of the distribution of the populations relative to specific watershed sensitivities to acidification. In the process of selecting new sites for reestablishment of cutthroat populations, watershed acid neutralizing capacity should also be considered among the selection criteria. The current distributions of the Colorado River cutthroat (*S. c. pleuriticus*) and the greenback cutthroat (*S. c. stomias*), relative to the marked differences in watershed sensitivity observed in RMNP exemplify this point. The Colorado River trout is native to the upper Colorado River basin (Figure 28) and efforts are being made to reestablish this fish in headwater sections located in RMNP. The greenback occupies the headwaters of the Arkansas and South Platte drainages (Figure 29), on the eastern side of the Continental Divide. Comparable efforts have been made to reintroduce this form into these areas of the Park. The higher alkalinities in the upper Colorado drainage would certainly favor the maintenance of *S. c. pleuriticus* in the advent of increased acid deposition, whereas the low alkalinities on the other side of the Divide would probably not inhibit acidification of the greenback's prime habitat. Behnke's and Zorn's (1976) prophetic suggestion that the greenback trout may be the most vulnerable of all western trouts to extinction, would likely be realized with acidification.

In addition to distribution, there are species specific life history characteristics that must be considered in assessing potential sensitivity to acidification. All of the interior western trouts of the genus *Salmo* have basically similar life histories. They spawn in the spring when water temperatures reach 5.5-9.0°C, which can be anywhere from early April to June or July, depending on latitude and elevation. All are obligatory stream spawners and fry emergence occurs in early to mid-summer. Growth, maturation, and fecundity are variable, depending on prevailing temperature regimes and productivity of the local habitats (Behnke and Zorn 1976). The basic life history pattern outlined above is markedly different from that exhibited by salmonid populations inhabiting waters of eastern North America and Scandinavia, where acidification impacts have been described (Schofield 1976; Muniz and Leivestad 1980). The predominant salmonid species in these areas

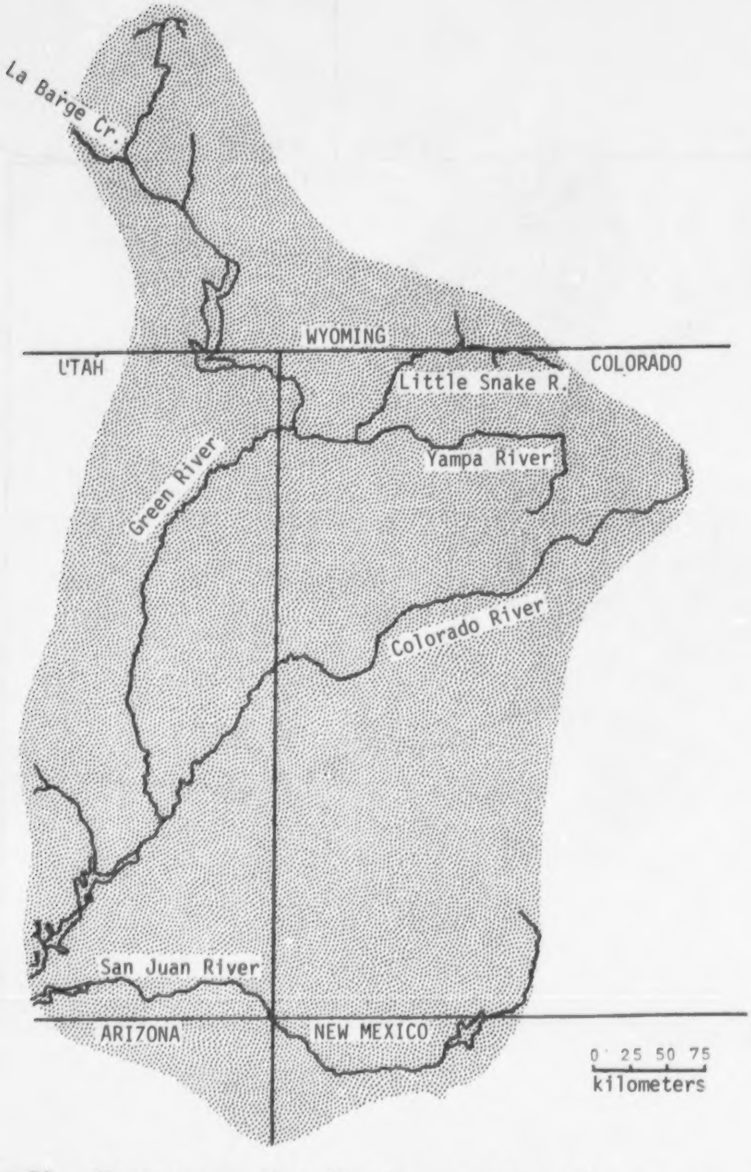

La Barge Cr.
WYOMING
UTAH
COLORADO
Little Snake R.
Yampa River
Green River
Colorado River
San Juan River
ARIZONA
NEW MEXICO
0 25 50 75
kilometers

Figure 28. Indigenous distribution of Salmo clarki pleuriticus (from Behnke and Zorn 1976).

(Salvelinus fontinalis, Salvelinus namaycush, Salmo trutta, and Salmo salar) are all fall spawners and either stream or lake spawning may be locally prevalent. Fry emergence for these species is in early spring, often coinciding with snowmelt periods when water quality is very poor in acidified areas. The fry (particularly during and shortly after hatching) of most of these species have also been found to be physiologically more sensitive to acidification

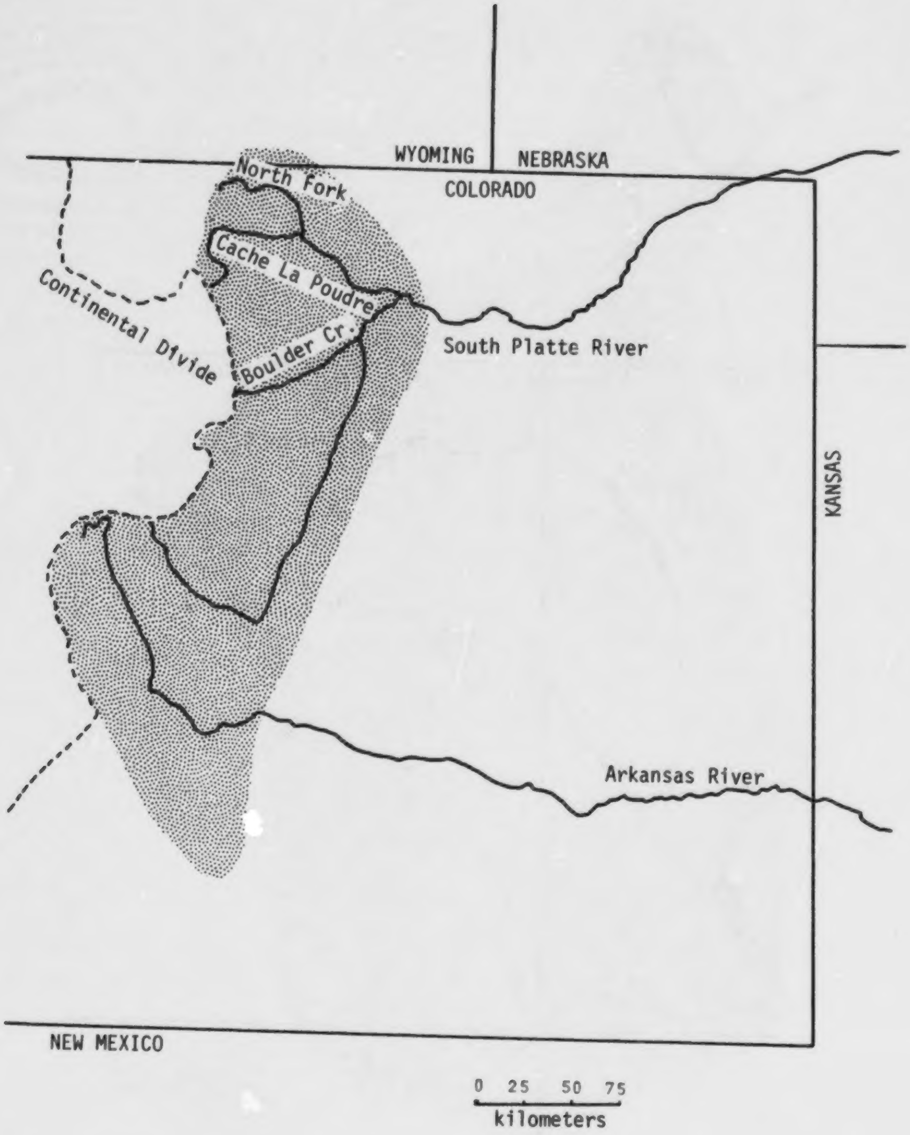

WYOMING
NEBRASKA
COLORADO
North Fork
Cache La Poudre
Continental Divide
Boulder Cr.
South Platte River
KANSAS
Arkansas River
NEW MEXICO
0 25 50 75
kilometers

Figure 29. Indigenous distribution of _Salmo_ _clarki_ _stomias_ (from Behnke and Zorn 1976).

than either embryos or older fish (Spry et al. 1981; Baker and Schofield 1980). For these reasons, the early life history stages of development have been identified as critical periods for survival in acidified habitats. Given the different life history pattern of the western _Salmo_ sp. and uncertain water quality conditions that might prevail during the early life history of these fish, under an acidification regime, it is difficult to extrapolate these findings from eastern North America and Scandinavia to the Rocky Mountain region. Water quality conditions would be more favorable for cutthroat fry if episodic acidification were to occur before hatching.

A more likely critical period for the headwater populations of this species might be during late winter and early spring, prior to or during spawning. Studies by Johnson and Webster (1977) demonstrated a marked avoidance of acidic water by spawning brook trout and Flick et al. (1982) noted a tendency for emigration of brook trout populations from lakes during episodes of acidic snowmelt. These latter observations are particularly relevant in terms of the known propensity for emigration by cutthroat populations inhabiting headwater streams subject to unfavorable winter temperature extremes (Bjornn 1971). According to Behnke and Zorn (1976), this was also the cause of a failed transplant of greenback trout in the North Big Thompson River in RMNP, where all the fish migrated downstream over a barrier during the winter months. A dense brook trout population below the barrier made it doubtful that the cutthroat population could sustain itself there. These behavioral responses to adverse environmental conditions suggest a subtle, but potentially devastating mechanism whereby even relatively minor acidification excursions in headwater trout refugia could lead to population extermination. Behavioral studies would be needed to define thresholds of acidification that induce avoidance in the form of downstream migration. It is quite likely that these thresholds (e.g., in terms of pH change) would be much lower than those determined by classical bioassay for definition of dose-response functions, where response is death or acute physiological stress.

As noted above, the relevance of any discussion of species specific dose-response functions, as usually defined, is somewhat questionable at this point, given the uncertainties in determining critical life history stages and population/community level responses. However, there are some potentially important, physiological level questions that need to be considered in defining the sensitivity of this species to acidification. Most comparisons of relative tolerance to acidity among salmonid species indicate that the rainbow trout (which is closely related to the cutthroat) is the most sensitive to low pH (Haines 1981). However, no studies have yet been conducted with the cutthroat to define its relative tolerance. Intraspecific variation in acid tolerance to acidity has been observed in brook trout (Flick et al. 1982) and brown trout (Gjedrem 1976), and the marked polytypic character of S. clarki (Trojnar and Behnke 1974) suggests that it might also exhibit significant variation in acid tolerance among the defined subspecies. Determination of the extent of this variation in acid tolerance among the extant populations in the Rocky Mountain region would be potentially useful for rehabitation programs, in the event of acidification.

The potential for aluminum mobilization by acidification in Rocky Mountain watersheds is uncertain, but probably not as great as in eastern forested systems where soils exhibit marked accumulations of amorphous forms of aluminum that are readily mobilized by acidic deposition (Cronan and Schofield 1979). The enhanced toxicity of acidified waters containing aluminum is well documented (Schofield and Trojnar 1980) and if aluminum mobilization is not an integral facet of the acidification process in Rocky Mountain soils, then comparisons of biological responses between the two areas would be further complicated by significant differences in solution chemistry.

Another important difference in solution chemistry between Rocky Mountain waters and those of eastern North America are the levels of dissolved calcium. The low calcium levels in the headwaters of the Rockies are more similar to the alpine waters of Scandinavia, than those of eastern North America. The significance of calcium as a mediator of gill membrane permeability and acid stress was noted by Brown (1981). Below 1 mg/l of calcium (typical for many of the Rocky Mountain headwaters) trout would be susceptible to acid induced osmoregulatory stress at much higher pH levels than populations inhabiting higher (>2 mg/l, typical for eastern waters) calcium waters. However, potential adaptation (acclimation) of resident trout populations to low calcium environments might ameliorate expected acid stress responses (Guthrie 1981). Again, it is difficult to generalize dose-response function when dealing with fish populations that have evolved under unique environmental conditions. The intraspecific genetic diversity of Salmo clarki is quite remarkable, but the potential adaptability of the genotypes of acidified environments remains to be determined.

CONCLUSIONS

INTRODUCTION

This section summarizes the conclusions reached concerning the four major objectives outlined in the introduction. The first two sections are specific to the two areas studied, RMNP and YNP. The third section evaluates the results of the water chemistry studies in terms of effect on several species of fish important to this region. Finally, the assessment of sensitivity of lakes and streams to acidification in the Rocky Mountain Region in general is based on studies in each of the two Parks.

ROCKY MOUNTAIN NATIONAL PARK

Soils and Geology

1. The soils of the Rocky Mountain National Park at the higher elevations (above 9,000 feet) are only slightly developed. They have surface organic horizons in some cases and usually have a darkened A-horizon underlain by slightly weathered material derived from granite, diorites and other rocks low in bases. The soils are coarse, low in clay, low in base cations and relatively acid (modal pH 5.2). The organic matter provides most of the cation exchange capacity and there is no evidence of sulfate adsorption capacity.
2. The physical properties of these soils--coarse, high in sand, low in clay, and steeply sloping--promote rapid movement of water to the streams and lakes.
3. The low base saturation, low pH and low cation-exchange capacity provide little opportunity for neutralizing the acidic inputs or providing significant alkalinity to the water system.
4. The soil itself is probably resistant to rapid acidification due to the abundance of relatively unweathered minerals.

Surface Water Chemistry

1. Primary mineral weathering appears to be the dominant mechanism determining the concentrations of base cations, silica and alkalinity throughout the Park. Factor analysis shows that the primary

mineral weathering of oligoclase and biotite accounts for almost 50% of the variance in stream chemistry in areas underlain by granite and biotite gneiss and schist. In areas that contain tertiary intrusive bedrock, the mineral weathering of mafic materials, sulfur bearing minerals, and oligioclase account for more than 50% of the variance in stream chemistry.

2. Atmospheric deposition is the primary source of chloride and nitrate in the streams of the Park. Atmospheric deposition is also the primary source of sulfate in the Park waters, with the exception of the Upper Colorado and Upper Fall River basins where the weathering of sulfur bearing minerals is a source of sulfate. Chloride and sulfate are relatively constant with elevation, while nitrate concentrations are highest above the timberline, where biological activity is lowest. Atmospheric deposition is also a significant source of streamwater C_B, a result of deposition of airborne dust and salts from the dry, windy, regions upwind of the Park.

3. Most of the waters in the study watershed have alkalinities of <100 μeq/l. The alkalinities are lowest at higher elevations. The waters of Glacier Gorge and Ypsilon Creek are extremely sensitive. Those of Roaring River and Upper East Inlet watersheds are very sensitive with alkalinities of <100 μeq/l. The waters of Lower East Inlet and the higher elevations of Upper Fall River watersheds are slightly higher with alkalinities <200 μeq/l. The waters in the lower elevations of Upper Fall River watershed are non-sensitive with alkalinities >200 μeq/l.

4. Based on the current concentrations of sulfate, nitrate, base cations and alkalinity we estimate that the waters of Glacier Gorge, Loch Vale, East Inlet and Ypsilon Creek watersheds may have suffered a small loss of alkalinity (<10 μeq/l). We estimate that the waters in the Upper Colorado, Upper Fall River and Roaring River watersheds have suffered no loss of alkalinity.

5. If precipitation in Rocky Mountain National Park becomes as acidic as in the eastern United States, we estimate that in the worst case (i.e., if the increase in acidic deposition does not cause an increase in base cation loss from the watershed), most of the lakes in Rocky Mountain National Park will become acidified below pH 4.7. At the other extreme, if for every μeq/l increase in acid sulfate in the waters there is a 0.4 μeq/l increase of base cation in the waters, we estimate using the Henriksen nomograph that the majority of lakes will become transitional and only a few will reach acid status. The low ion-exchange capacity of the soils in the Park and the resistance of the bedrock to chemical weathering indicates that the increase in base cation concentrations with increased acidic deposition in the Park will be low and that with increasing acidic deposition many of the lakes will shift from a bicarbonate towards an acid status.

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YELLOWSTONE NATIONAL PARK

1. The region-chemistry t-tests and alkalinity-elevation plot showed that, after other influences are accounted for, surficial geology and elevation are correlated to water chemistry. Rhyolite, the dominant bedrock formation in the park, appears to be the most sensitive (conferring the least buffering capacity), although the subalpine (mean elevation = 2651 m) lakes located in the andesitic-volcaniclastic rocks of the northwestern corner also may be potentially sensitive.

2. Lakes found in other regions of the park--the andesitic Absaroka Mountains, the mixed metamorphic Gallatin and Beartooth ranges--appear not immediately sensitive to acidification by acid precipitation (alkalinities generally above 500 μeq/l). These findings are corroborated by a streamwater chemistry study in the Absaroka Mountains (Miller and Drever 1977b), where mean alkalinity for 14 stream samples in the Shoshone River Basin was found to be 650 μeq/l.

3. Finally, no clear trends in surface water chemistry appear from examination of historical data. It is suggested that if any chemistry changes have occurred at all, these are limited to the northwest corner lakes. Since estimated "baseline" (precipitation-derived) sulfate levels in Yellowstone lakes are still fairly low in comparison to those levels in known acidified lakes throughout the continent, any acidification that has occurred is minimal. Most of the park lakes appear well protected from acidification in the future. For the present, the dilute lakes of the rhyolite bedrock and Fall River basalt region, as well as the Specimen Creek drainage basin lakes, are most vulnerable to changes in chemistry by acid rain.

EFFECTS OF CURRENT AND FUTURE ACIDIFICATION LEVELS IN FISH POPULATIONS IN YELLOWSTONE AND ROCKY MOUNTAIN NATIONAL PARKS

1. Currently, there is no evidence of chronic acidification in Rocky Mountain waters that would be detrimental to fish survival.

2. The very low base cation concentrations observed in the headwater drainages of RMNP suggests extreme sensitivity to acidification. Fish populations present in these low calcium waters may be particularly susceptible to osmoregulatory stress from episodic acidification.

3. The few remaining native trout (*Salmo clarki*) populations located in interior regions of the Rocky Mountains persist only in small, isolated headwater drainages. The cutthroat coexists with and dominates introduced species only in cold, headwater situations. Displacement of these rare and endangered genotypes to headwater drainages also makes them most susceptible to potential acidification in these sensitive habitats.

4. Although a large proportion of the headwater lakes in YNP and other areas are historically fishless, and many are still in that condition, these waters represent potentially invaluable refugia for the reestablishment of endangered species.

5. Comparisons of alkalinity and bedrock geology in the upper Colorado and eastern Divide drainages in RMNP, suggests that the greenback trout (*Salmo clarki stomias*), which occupies the latter basins, is at potentially greater risk than the Colorado River cutthroat (*Salmo clarki pleuriticus*).

6. A comparison of the life history patterns of the western Salmo with eastern salmonids, in relation to seasonal changes in acidity, indicates that different life history stages may be impacted by acidification. Hatching and fry development have been identified as critical periods for the fall spawning eastern salmoids. However, early-late summer emergence of fry in the western *Salmo* populations (spring spawners) indicates this may be a less critical life history stage.

7. Avoidance response, in the form of downstream emigration, to episodic acidification in headwaters occupied by *S. clarki* is suggested as a more subtle, but potentially devasting impact of acidification in the Rocky Mountain watersheds.

8. The relative sensitivities of the cutthroat genotypes to acidification stress, capacities for adaption in low calcium water, and dose-response functions are currently unavailable.

SENSITIVITY EVALUATION OF THE CENTRAL ROCKY MOUNTAIN REGION

The examination of the geochemistry of Rocky Mountain National Park has shown that many areas in RMNP are sensitive to acidic deposition and that this sensitivity is primarily determined by bedrock geology. In addition, sensitivity varies inversely with elevation in watersheds with consistent geology. The results of the evaluation of the existing data in YNP, though not so definitive, corroborate the general findings in the RMNP studies. An evaluation of the sensitivity of the Central Rocky Mountains (Colorado and Wyoming), using geologic maps and elevation, can be provided based on this information.

The analyses in RMNP show that watersheds underlain by granite and biotite gneiss and schist are equally sensitive to acidic deposition. The lakes and streams in these watersheds had alkalinities <200 µeq/l, while the waters at higher elevations (>3300 m) were very sensitive (alkalinity ≤ 100 µeq/l). The Upper Colorado River Basin and the Upper Fall River Basin contain tertiary intrusive rocks in their drainage, resulting in low (alkalinity >200 µeq/l) sensitivity. In YNP, low-alkalinity or sensitive lakes were found in regions underlain by rhyolite flows or basalt and andesitic-basaltic flows (USGS 1977; Tweto 1979).

The analysis of sensitive aquatic systems in the Central Rocky Mountain Region has been accomplished by extrapolating the results from RMNP and thus delineates areas underlain by granite biotite gneiss and schist and similar gneisses and schists (Figures 30 and 31). Areas underlain by these formations are classified as sensitive (alkalinity <200 µeq/l), lakes and streams located at higher elevations (>3300 m) can be classified as very sensitive (alkalinity ≤100 µeq/l). Although areas of YNP have a limited number of moderately sensitive lakes (>200 µeq/l), areas underlain by tertiary intrusive rocks are generally classified as nonsensitive (alkalinity >200 µeq/l).

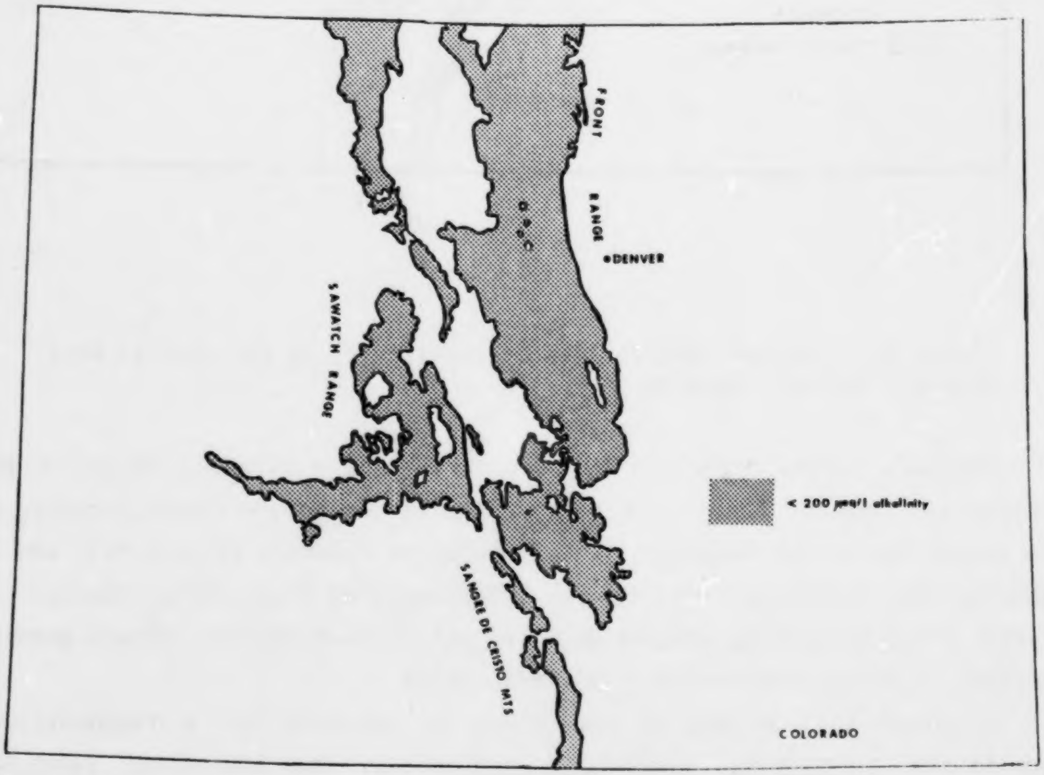

Figure 30. Spatial distribution of sensitivity in the central Rocky Mountain Region: Colorado.

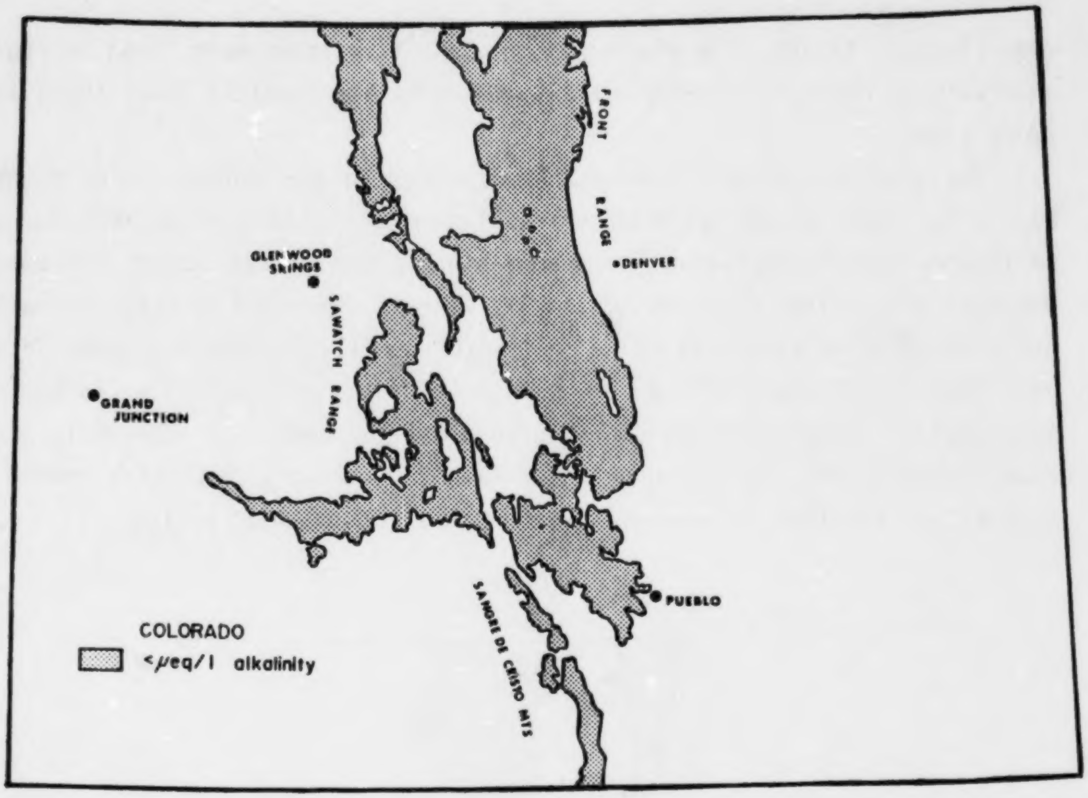
FRONT RANGE
DENVER
GLENWOOD SPRINGS
SAWATCH RANGE
GRAND JUNCTION
PUEBLO
SANGRE DE CRISTO MTS
COLORADO
<μeq/l alkalinity

Figure 31. Spatial distribution of sensitivity in the central Rocky Mountain Region: Wyoming.

Mountain ranges underlain by rock formations similar to those in RMNP include the Sawatch Range, the Front Range (Lovering and Goddard 1950), and the Sangre de Cristo Mountains (Litsey 1958) in Colorado (Figure 30), and the Medicine Bow Mountains (Hill et al. 1968) and Wind River Range (Bassett and Giletti 1963) in Wyoming (Figure 31). All of these mountains contain granite, gneisses, schists, and tertiary intrusive rocks.

Although this method of evaluation is adequate for a regional-scale sensitivity assessment, sensitivity evaluations for individual lakes and streams must be carried out on a drainage by drainage basis. Small outcrops of highly weatherable rocks, too small to be seen on regional-scale maps, may have an overwhelming influence on the sensitivity of a watershed. This is the case in the Upper Fall River Basin in RMNP. The bedrock in this basin is primarily granite and biotite gneiss and schist. However, a small deposit of tertiary intrusive rock at the head of the watershed gives the Fall River a relatively high alkalinity (>200 μeq/l). Differences in hydrologic flow path and soil development may also dominate sensitivity on a local scale.

RECOMMENDATIONS FOR RESEARCH AND MANAGEMENT

INTRODUCTION

While these studies and most others would indicate that areas of the Rocky Mountain West were not experienceing significant impacts from acid deposition, they also demonstrate that many headwater lakes and streams are very sensitive (alkalinities < 200 µeg/e). It is therefore believed prudent to undertake some long term programs to more fully assess the current status of both deposition and surface water chemistries and to develop some long term measurement programs. In addition strategies should be developed to protect indigenous fish populations in the advent that this area does experience increased sulfate and nitrate deposition. The following recommendations are formulated to address these issues.

ROCKY MOUNTAIN NATIONAL PARK AND ROCKY MOUNTAIN REGION

1. Long term watershed experiments should be established at several points in the Rocky Mountain Region. At minimum, routine sampling (on at least a bi-weekly basis and in the spring, every 2 to 3 days) should be performed. The samples should be analyzed for all major inorganic constituents, DOC, aluminum, alkalinity and total acidity. Based on the research of this project, we recommend that the Glacier Gorge watershed in RMNP be considered for long-term monitoring. (As a result of this recommendation the National Park Service is now conducting a long-term study in the Loch Vale subbasin of the Glacier Gorge watershed.)

2. Additional surveys of water chemistry should be performed in mountainous areas not only in the Rocky Mountain region but also in other mountainous areas of the western United States. It is most probable that the acidity of precipitation will increase in future years and it will be to our benefit to obtain background data at this time.

3. The results from the watershed studies should be made available to research groups having models on watershed response to acidic deposition. This will ensure that if there are pecularities about western watersheds, that the models will be developed with those pecularities taken into account.

4. Since one of the differences between the Rocky Mountain region and other regions experiencing acid rain is the greater importance of nitric acid relative to sulfuric acid, watershed studies should be designed to take this into account.

5. A greater effort must be made to determine the rate of dry deposition of neutral salts (e.g., $CaSO_4$).

YELLOWSTONE NATIONAL PARK

1. Future studies in Yellowstone National Park should concentrate on those regions which this report has determined as potentially sensitive to acidification. In particular, reliable water chemistry from the Specimen Creek drainage basin is necessary to determine if these lakes are indeed as dilute as indicated.

2. A more intensive sampling of the low alkalinity lakes (i.e., several alkalinity measurements over the course of a year) would indicate seasonal fluctuations in alkalinity and provide a more complete estimate of sensitivity. It is suggested that the analytical technique used to determine alkalinity of these lakes be one designed specifically for low alkalinity water, i.e., Gran's plot or double endpoint potentiometric titration.

3. Finally, a survey of the headwater streams of the Park, particularly those in sensitive regions or with important fisheries, is necessary for a complete understanding of the response of Yellowstone to potential acidification.

FISHERY RESEARCH AND MANAGEMENT

1. The potential sensitivity to acidification, of watersheds currently occupied by endangered or threatened populations of *S. clarki* or of watersheds considered as potential candidate sites for reintroduction, should be determined and given consideration in recovery plans for the species.

2. Any further experiments designed to develop dose-response functions for interior western *Salmo clarki* populations, should consider the possibility of significant variations in tolerance of this polytypic species. Additionally, these responses to acidification need to be determined in very low calcium media, typical of the headwater habitats of this species.

3. The behavioral responses and emigration tendencies of *S. clarki* populations exposed to episodes of acidification should be determined experimentally.

4. The potential for aluminum mobilization in Rocky Mountain watersheds exposed to increased acid deposition should be determined.

5. Future studies of winter and spring lake and stream chemistry in headwater catchments should also evaluate movement of trout populations, in response to chemical change.

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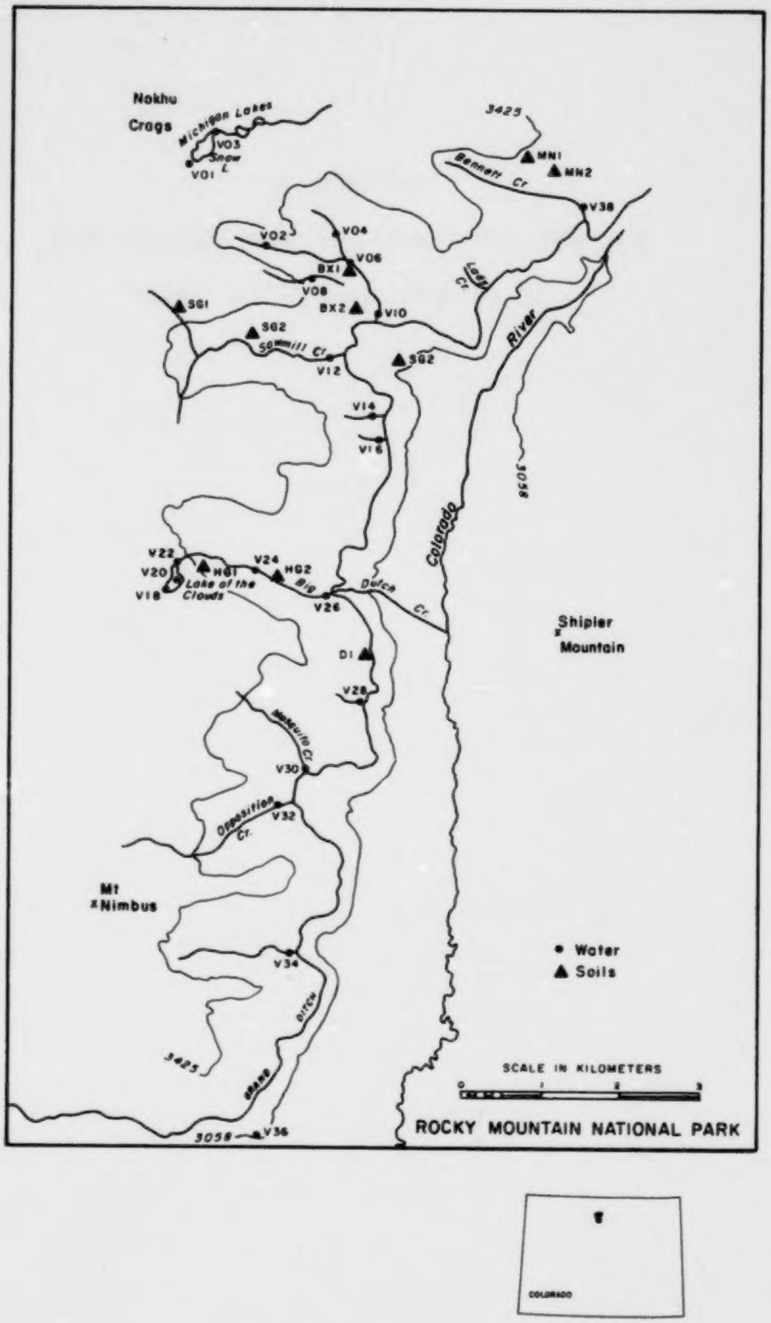
APPENDIX A

SOIL AND WATER CHEMISTRY SAMPLING SITE MAPS, ROCKY MOUNTAIN NATIONAL PARK


Nokhu Crags
Michigan Lakes
V03
Snow L
V01
3425
MN1
MN2
Bennett Cr
V38
V02
V04
V06
BX1
V08
BX2
V10
SG1
SG2
Sawmill Cr
V12
SG2
Lost Cr
River
V14
V16
3058
Colorado
V22
V20
HG1
V24
HG2
Lake of the Clouds
Big
Dutch
Cr
V18
V26
Shipler Mountain
D1
V28
Mosquito Cr
V30
Opposition Cr
V32
Mt Nimbus
V34
Water
Soils
Ditch
3425
Grand
3058
V36
SCALE IN KILOMETERS
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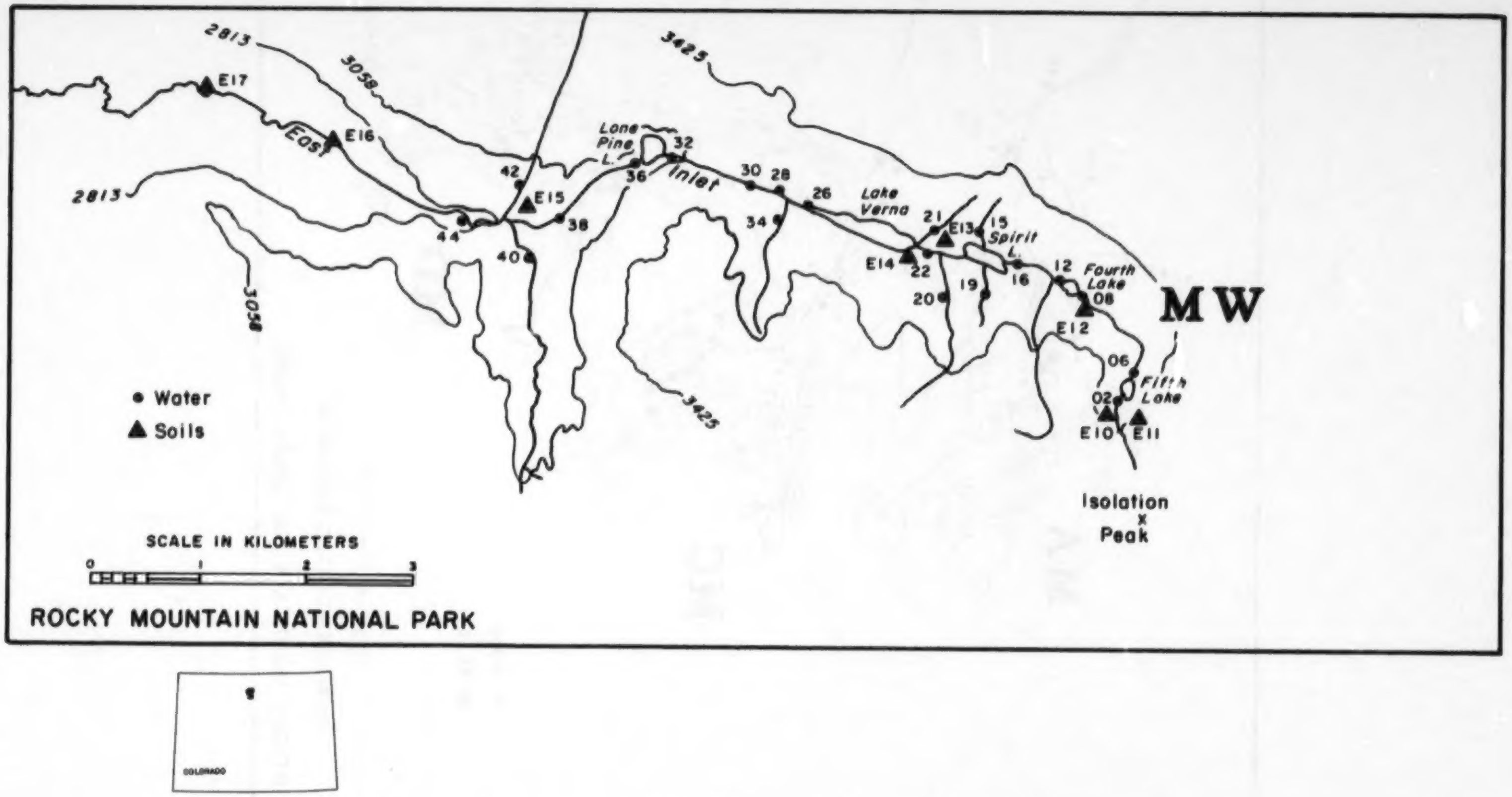
ROCKY MOUNTAIN NATIONAL PARK
COLORADO

Figure A-1. Soil and chemistry sampling sites in Upper Colorado basin, RMNP.


2813
3058
3425
E17
E16
East
42
E15
44
40
38
Lone Pine L.
36
32
Inlet
30
28
26
34
Lake Verna
21
E13
15
Spirit L.
E14
22
20
19
16
12
Fourth Lake
08
E12
MW
06
Fifth Lake
02
E10
E11
Isolation x Peak
• Water
▲ Soils
SCALE IN KILOMETERS
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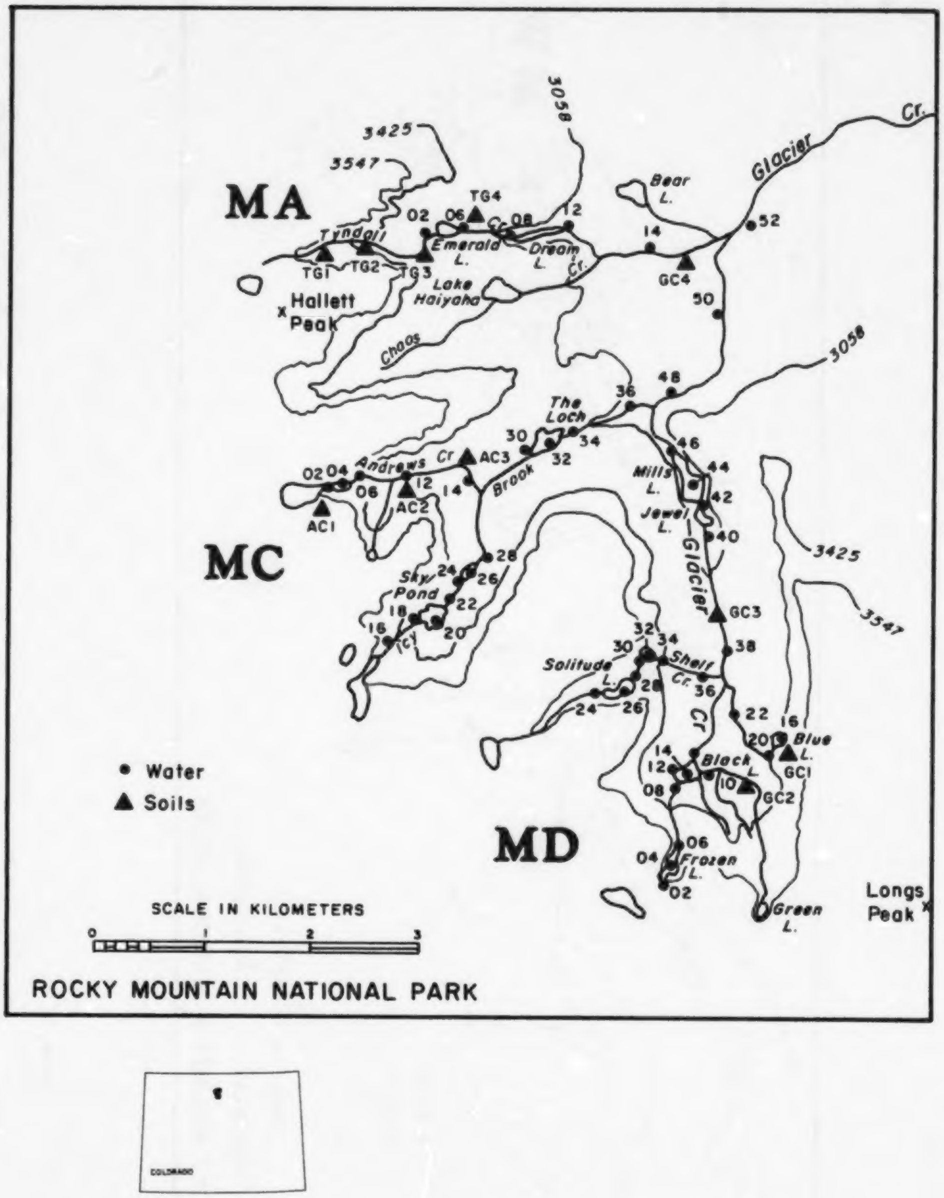
ROCKY MOUNTAIN NATIONAL PARK
COLORADO

Figure A-2. Soil and chemistry sampling sites in East Inlet basin, RMNP.


MA
MC
MD
3425
3547
3058
Glacier
Cr.
Bear L.
Tyndall
Emerald L.
Dream L.
Cr.
Lake Haiyaha
Hallett Peak
Chaos
TG1
TG2
TG3
TG4
02
06
08
12
14
GC4
52
50
48
36
The Loch
30
34
32
Andrews Cr
AC3
AC1
AC2
02
04
06
12
14
Brook
Mills L.
Jewel L.
46
44
42
40
Glacier
GC3
38
28
Sky Pond
24
26
22
18
16
20
Solitude L.
30
32
34
28
26
24
Shelf Cr.
36
Cr
22
16
20
Blue L.
GC1
Black L.
14
12
10
08
GC2
06
04
Frozen L.
02
Green L.
Longs Peak
• Water
▲ Soils
SCALE IN KILOMETERS
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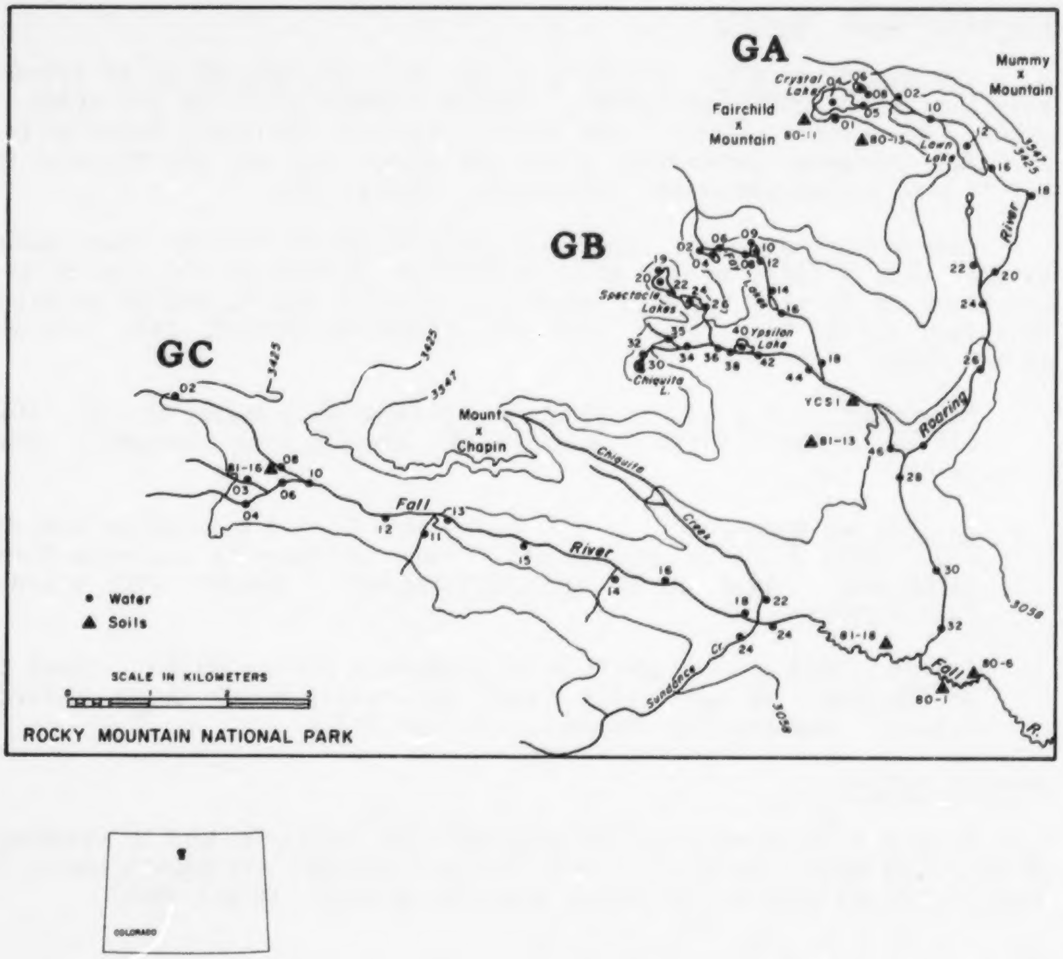
ROCKY MOUNTAIN NATIONAL PARK
COLORADO

Figure A-3. Soil and chemistry sampling sites in Glacier Gorge basin, RMNP.


GA
GB
GC
Mummy Mountain
Fairchild Mountain
Crystal Lake
Lawn Lake
Spectacle Lakes
Ypsilon Lake
Chiquita L.
Mount Chapin
Chiquita Creek
Roaring River
Fall River
Sundance Cr
Fall R.
80-11
80-13
81-13
81-16
80-6
80-1
YCS1
3547
3425
3050
Water
Soils
SCALE IN KILOMETERS
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ROCKY MOUNTAIN NATIONAL PARK
COLORADO

Figure A-4. Soil and chemistry sampling sites in Fall River basin, RMNP.

APPENDIX B

SOIL LABORATORY PROCEDURES, PROFILE DESCRIPTIONS AND CHEMICAL ANALYSES

SOIL LABORATORY ANALYSIS PROCEDURES

Cation Exchange Capacity

Extractable acidity. To 10 g of air dry soil add 100 ml of extraction solution ($BaCl_2$, triethanolamine). Stopper, shake well, and let stand overnight. Run blank. Filter, wash with extracting solution. Bring up to 250 ml. Add indicator (bromcresol green and methyl red) and titrate with 0.2 N HCl to pink orange end-point. Calculate. (Black 1965)

Base extraction. Use macerated paper in 60 ml fritted glass funnels. Extract with a total of 100 ml 1 N ammonium acetate pH 7.0 (allow to sit overnight in 30 ml extracting solution). Run Ca, Mg, K, and Na on extract. Calculate C.E.C. and report in meq. Calculate percent base saturation. (Black 1965)

Potassium: 1.5 g soil in 15 ml of 1 N ammonium acetate, pH 7.0. Shake 5 min at 200 opm. Filter. Read on AA. Compare with standards. (Carson 1975)

Calcium and magnesium: To 1.5 g soil add 15 ml 1 N ammonium acetate pH 7.0. Shake 5 min at 200 opm and filter. Dilute with Lanthanum Chloride (1500 ppm). Read on AA Spectrophotometer. Compare with standards. (Walsh 1971).

Sodium: To 5 g soil add 15 ml 1 N ammonium acetate pH 7.0. Shake 5 min at 200 opm. Do not filter. Read supernatant liquid on AA Spectrophotometer. Compare with standards. (Walsh 1971).

Organic Matter

Oxidize with potassium dichromate and conc. sulfuric acid by standing for 30 min; add water, phosphoric acid, sodium flouride, and diphenylamine indicator. Titrate with 0.5 N ferrous ammonium sulfate. (Black 1965).

pH

1:1 soil to water volume. Mix 5 seconds. Let stand 10 min. Stir, read pH with pH meter. (McLean 1975).

Particle Size

Samples are sieved to remove particles larger than 2 mm. The remaining sample is dispersed with sodium hexametaphosphate, placed in settling containers and subsampled at appropriate intervals with a pipette. The subsample is dried at 105 C and weighed. (Franzmeier et al. 1977).

Loss on Ignition (LOI)

Ovendried (105 L) samples are ignited in a muffle furnace at 550 C and the loss in weight is determined. In soils with low clay contents, the loss is a valid estimate of organic matter. (Black 1965).

Sulfate Absorption

Soil samples (10 g) were equilibrated with 25 ml of dilute K_2SO_4 solution at a pH of 4.1. The solutions were initially at 1, 5 and 10 mg sulfur per liter. After filtration the solutions were analyzed for remaining sulfate utilizing an indirect Atomic Absorption method. (Øien 1979).

Table B-1. Particle size distribution of soil samples.

Location[a]	Depth (cm)	>2 mm (%)	Percent of less than 2 mm			Textural class
			Sand	Silt	Clay	
TG-1	0-11	55	68	27	5	SL
TG-1	11-25	60	82	13	5	S
TG-2	0-17+	0	35	55	10	SIL
TG-4	0-5	1	21	66	13	SIL
TG-4	5-11	2	21	60	19	SIL
TG-4	11-24	8	35	46	19	L
AC-1	0-8	--	52	39	9	L
GC-1	Talus	66	91	6	3	LS
GC-2	24-50+	56	83	14	3	S
GC-3	0-6	3	23	70	7	SIL
GC-3	9.5-30	19	75	15	10	SL
EI-1	Talus	56	65	27	8	SL
EI-2	0-9	0	20	75	5	SIL
EI-3	3-13	58	39	45	16	L
EI-3	13-28+	76	18	70	12	SIL
EI-5	0-16	8	43	35	22	L
EI-5	16-31+	10	43	34	23	L
EI-6	0-4	23	51	41	8	L
BX-1	0-51+	53	50	35	15	L
HG-2	0-5	7	34	54	12	SIL
HG-2	5-35+	70	64	23	13	SL
MN-1	Talus	43	70	23	7	SL
IL-2	6-0	--	43	54	3	SIL
L80-1	5-0	--	23	73	4	SIL
L80-1	0-19	--	77	19	4	S
L80-1	19-54	--	93	4	3	LS
L80-1	54-80	--	84	12	4	S
L80-1	80-85+	--	80	16	4	S
L80-6	0-18	--	63	28	9	S
L80-6	18-50	--	49	46	5	SL
L80-6	50-80+	--	85	11	4	S
L80-11	0-35+	--	85	11	4	S
L80-13	Muck	--	37	56	7	SIL
L80-13	Gravel	--	77	16	7	S
L81-13	0-1	--	55	37	8	SL
L81-13	1-18	--	61	32	7	SL
L81-13	18-46	--	62	24	14	SL
L81-13	46-60+	--	73	17	10	SL
L81-16	31-42+	--	32	62	6	SIL
L81-18	0-24	--	68	25	7	SL
L81-18	24-36	--	78	17	5	S
L81-18	36-59+	--	68	27	5	SL
YCS-1	4-11	--	62	31	7	SL
YCS-1	11-21	--	83	13	4	S
YCS-1	21-36	--				
YCS-1	45-60+	--	82	15	3	S

[a] See maps Appendix A.

Table B-2. Soil chemical analyses[a].

Site I.D.[b]	Depth (cm)	% LOI	% OM	pH	Exch. Ca	Exch. Mg	Exch. K	Exch. Na	Exch. H	CEC	Base sat.	Exch. bases
TG-1	0-11	13.8	10.2	6.0	14.28	2.12	0.366	0.040	11.42	28.23	59.5	16.5
TG-1	11-25	4.20	3.40	5.7	3.03	0.556	0.119	0.035	4.35	8.09	46.23	3.7
TG-2	30-0	47.2	55.20	5.2	6.59	0.630	0.305	0.131	41.10	48.76	15.7	7.7
TG-2	0-17[a]	14.2	9.03	4.3	6.00	0.880	0.181	0.136	41.27	48.47	14.9	7.2
TG-3	Talus	2.16	1.30	5.2	5.25	1.01	0.194	0.043	10.28	16.78	38.7	6.6
TG-4	3-0	32.6	25.0	4.6	4.20	0.980	0.875	0.078	41.88	48.01	12.8	6.2
TG-4	0-5	13.0	10.4	4.8	0.936	0.346	0.334	0.077	38.31	40.00	4.2	1.7
TG-4	5-11	11.4										
TG-4	11-24	9.21										
TG-4	24-36	4.92	3.19	5.0	0.204	0.034	0.075	0.031	25.95	26.29	1.3	0.3
AC-2												
AC-3	5-0	60.9	65.5	5.5	9.15	3.29	3.52	0.732	33.86	50.55	33.0	18.2
AC-3	0-9.5	8.57	5.45	5.1	1.84	0.425	0.209	0.342	17.44	20.26	13.9	2.8
AC-3	9.5-12.5	11.2										
AC-3	12.5-50+[a]	9.18	1.62	4.9	1.84	0.731	0.060	0.279	19.93	22.84	12.7	2.9
GC-1	Talus	2.01	1.62	5.2	1.10	0.20	0.095	0.030	2.44	3.87	37.0	1.4
GC-2	4-0	32.5	46.1	5.1	31.27	6.71	3.58	0.147	39.47	81.18	51.4	41.6
GC-2	0-24	5.85	4.33	5.2	2.93	0.538	0.169	0.035	5.75	9.42	39.0	3.7
GC-2	24-50[a]a	3.16	3.25	5.0	1.70	0.217	0.072	0.052	4.48	6.52	31.3	2.0
GC-3	5-0	75.8	62.7	4.3	0.963	0.535	0.672	0.107	45.29	47.57	4.8	2.3
GC-3	0-6	28.0	28.5	4.2	0.315	0.438	0.467	0.187	41.03	42.44	3.3	1.3
GC-3	6-9.5	18.0										
GC-3	9.5-30	3.52	2.67	4.6	0.101	0.063	0.058	0.039	12.13	12.40	2.2	0.2
GC-4	4-0	75.5	65.4	4.9	14.58	2.07	1.25	0.131	34.07	52.10	34.6	18.0
GC-4	0-4	9.32	6.14	4.9	4.12	0.927	0.633	0.134	21.80	27.61	21.0	5.9
GC-4	4-10	2.21	0.911	5.1	1.11	0.286	0.101	0.035	6.17	7.70	19.9	1.5
GC-4	10-46[a]	2.76										
EI-0	5-0											
EI-0	0-3											
EI-0	3-13											
EI-0	13-24											
EI-0	24-35[a]											
EI-1	Talus	6.99	6.44	5.1	2.63	0.556	0.311	0.039	12.13	15.67	22.6	3.5
EI-2	23-0	51.9	47.7	4.7	7.53	1.29	0.937	0.369	42.06	52.19	19.4	10.1
EI-2	0-9	19.7	17.9	4.8	3.15	0.315	0.086	0.132	35.04	38.72	9.5	3.7
EI-2	9-27[c]	11.2	7.74	4.8	2.27	0.224	0.040	0.080	27.46	30.07	8.7	2.6

Table B-2. (continued)

Site[b] I.D.	Depth (cm)	% LOI	% OM	pH	Exch. Ca	Exch. Mg	Exch. K	Exch. Na	Exch. H	CEC	Base sat.	Exch. bases
EI-3	12-7	75.0	55.3	5.9	46.44	5.40	1.11	0.126	26.37	79.45	66.8	53.1
EI-3	7-0	60.3	59.5	6.1	72.36	7.93	0.581	0.272	26.81	107.95	75.2	81.2
EI-3	0-3	29.7	27.6	6.3	50.83	5.80	0.412	0.214	22.43	79.69	71.9	57.3
EI-3	3-13	5.26										
EI-3	13-28[a]	2.67	2.17	5.9	8.99	1.30	0.129	0.083	4.73	15.23	68.9	10.5
EI-4												
EI-5	19-0	68.8	60.9	5.0	24.53	4.09	1.65	0.246	36.82	67.34	45.3	30.5
EI-5	0-16	6.70	5.34	5.5	10.82	1.88	0.726	0.111	15.09	28.63	47.3	13.5
EI-5	16-31[a]	5.36	4.93	5.6	8.96	1.63	0.647	0.121	14.88	26.24	43.3	11.4
EI-6	0-4	19.5										
EI-6	4-10	4.53										
EI-6	10-31[a]	5.02										
EI-7	20-0	18.8	17.1	5.1	8.76	1.88	0.383	0.434	23.48	34.94	32.8	11.5
EI-7	0-22	11.4	12.4	5.3	13.00	3.46	0.194	0.452	18.20	35.31	48.5	17.1
EI-7	22-37	3.84	1.98	5.5	10.71	2.98	0.042	0.288	6.23	20.25	69.2	14.0
EI-7	37-39[a]	3.82										
SG-1	Talus	6.63	3.14	5.2	7.34	2.04	0.458	0.044	12.45	22.33	44.2	9.7
SG-2	17-0	34.3	31.5	5.2	10.49	1.59	0.259	0.101	27.40	39.84	31.2	12.4
SG-2	0-17	3.66	2.15	5.2	3.40	0.717	0.138	0.052	8.95	13.26	32.5	4.3
SG-2	17-30	4.15										
SG-2	30-41[a]	7.09	2.57	5.1	2.53	0.556	0.124	0.070	15.42	18.70	17.5	3.3
SG-3	2-0	69.0	38.5	4.7	13.39	4.99	1.87	0.115	33.33	53.70	37.9	20.0
SG-3	0-5	4.48	2.66	4.5	1.92	1.60	0.285	0.066	18.29	22.16	17.5	4.0
SG-3	5-24[a]	5.75	2.60	4.9	0.909	0.286	0.223	0.062	17.47	18.95	7.8	1.5
BX-1	2-0	40.9	38.1	5.3	15.41	5.41	1.82	0.121	29.55	52.31	43.5	22.6
BX-1	0-51[a]	5.60	3.58	5.1	3.64	0.740	0.311	0.101	17.47	22.26	21.5	4.8
BX-1	14-16	6.62										
BX-2	Talus											
HG-1	Talus	5.42	2.34	5.8	6.57	0.841	0.376	0.048	9.66	17.50	44.8	8.1
HG-2	4-0	50.8	52.3	3.5	7.28	2.42	1.50	0.185	47.20	58.59	19.4	11.4
HG-2	0-5	19.9	18.5	4.3	1.02	0.425	0.393	0.137	34.87	36.85	5.4	2.0
HG-2	5-35[a]	5.50	2.41	5.1	0.505	0.185	0.093	0.062	19.5	20.38	4.2	0.8
D-1	3-0	48.0	31.1	5.4	23.32	5.56	1.17	0.106	31.2	61.53	49.2	30.1
D-1	0-11	11.2	7.96	5.6	14.79	4.08	0.602	0.115	19.3	38.89	50.4	19.5
D-1	11-21	4.52										
D-1	21-48[a]	4.68	1.26	5.7	7.47	2.27	0.311	0.070	10.89	21.01	48.2	10.1
MN-1	Talus	4.87	3.55	5.5	4.60	0.700	0.174	0.030	10.99	16.49	33.4	5.3

Table B-2. (concluded)

Site I.D.^{b}	Depth (cm)	% LOI	% OM	pH	Exch. Ca	Exch. Mg	Exch. K	Exch. Na	Exch. H	CEC	Base sat.	Exch. bases
MN-2	0-4	4.64	2.51	4.4	2.60	0.750	0.308	0.082	13.02	16.76	22.3	3.7
MN-2	4-40	3.45	1.16	5.2	2.32	0.639	0.336	0.114	12.13	15.54	21.9	3.5
MN-2	40-50^a	2.19										
IL-1	Talus	6.72	5.05	5.0	3.84	0.690	0.285	0.048	15.42	20.28	24.0	4.8
IL-2	6-0	35.8	27.7	5.0	25.24	5.92	1.07	0.125	22.85	55.21	58.6	32.2
IL-2	0-15	10.9	7.21	5.0	6.46	2.02	0.246	0.105	21.38	30.21	29.2	8.7
L80-1	5-0	42.3	28.79	5.9	24.48	4.67	0.641	0.044	20.13	49.97	59.7	29.8
L80-1	0-19	1.46	0.87	5.3	1.40	0.483	0.108	0.017	2.65	4.66	43.1	2.0
L80-1	19-54	0.92	0.31	5.3	0.80	0.183	0.079	0.030	1.02	2.11	5.17	1.0
L80-1	54-80	0.71	0.22	5.3	0.80	0.150	0.077	0.017	0.611	1.66	63.2	1.0
L80-1	80-85^a	0.66	0.08	5.8	0.70	0.20	0.051	0.013	0.407	1.37	70.3	1.0
L80-6	0-18	3.94	2.60	6.4	7.34	1.17	0.458	0.022	2.91	11.90	75.5	9.0
L80-6	18-50	1.44	0.38	6.8	2.80	0.700	0.090	0.030	0.814	4.43	81.6	3.6
L80-6	50-80^a	0.83	0.32	6.5	1.90	0.450	0.051	0.043	0.204	2.65	92.3	2.5
L80-11	0-35^a	2.39	0.27	5.5	4.10	1.333	0.072	0.126	2.65	8.28	68.0	5.6
L80-13	"Muck"	24.9	21.54	4.8	5.15	1.048	0.182	0.206	38.15	44.74	14.7	6.8
L80-13	Gravel	5.35	4.30	5.0	2.63	0.606	0.031	0.096	11.10	14.46	23.2	3.3
L81-13	0-1	5.84	3.96	5.8	5.60	0.800	0.346	0.052	9.16	15.96	42.6	6.8
L81-13	1-18	2.85	1.47	5.3	3.94	0.690	0.169	0.035	6.58	11.41	42.3	4.8
L81-13	18-46	2.60	0.65	5.2	1.21	0.455	0.194	0.057	10.28	12.20	15.7	1.9
L81-13	46-60^a	2.02	0.31	5.3	0.90	0.383	0.141	0.035	6.31	7.77	18.8	1.5
L81-16	0-10	76.8	72.9	5.0	7.83	3.27	1.28	0.327	35.00	47.7	26.6	12.7
L81-16	10-31	63.1	56.8	4.8	4.52	1.75	0.129	0.214	36.75	43.36	15.2	6.6
L81-16	31-42^a	27.0	21.7	4.7	6.80	2.58	0.098	0.242	28.72	38.44	25.3	9.7
L81-18	0-24	7.98	6.46	6.1	6.57	1.94	0.647	0.022	7.19	16.37	56.1	9.2
L81-18	24-36	1.14	0.83	6.1	2.40	0.567	0.172	0.017	1.42	4.58	69.0	3.1
L81-18	36-59^a	1.15	0.50	6.1	2.00	0.567	0.167	0.013	1.22	3.97	69.3	2.8
YCS-1	4-11	3.46	2.49	5.0	3.70	0.667	0.218	0.030	8.14	12.76	36.2	4.6
YCS-1	11-21	1.28	0.83	5.2	2.90	0.450	0.105	0.026	3.46	6.94	50.1	3.5
YCS-1	21-36^a	1.74	0.94	5.2	2.22	0.320	0.103	0.017	7.40	10.06	26.4	2.6
YCS-1	45-60^a	1.16	0.39	5.4	0.50	0.067	0.041	0.013	3.46	4.08	15.2	0.6
YCS-1^c	0-4	38.3										
YCS-1^c	36-60^a	0.72										

[a] From McFee (unpublished)
[b] See maps Appendix A.
[c] Film container samples.

APPENDIX C

WATER CHEMISTRY DATA, ROCKY MOUNTAIN NATIONAL PARK

The raw water chemical data collected in Rocky Mountain National Park are presented with the elevation of each sample site. Missing data are denoted by an asterisk. Sample location maps are included in Appendix A. The sample identification code follows:

GA	Roaring River	
GB	Ypsilon Creek	Fall River Basin
GC	Upper Fall River	
MA	Andrews Creek	
MC	Loch Vale	Glacier Gorge
MD	Glacier Gorge	
V	Upper Colorado River Basin	MW East Inlet

The sample code indicates whether the sample was taken from a stream (S), lake inlet (I), lake outlet (O), or lake surface (L). Replicate samples are denoted by an 'R' after the sample number.

The lake inlet and stream samples were used to calculate the mean concentrations of the major anions and cations for each subbasin.

Table C-1. Lake and stream pH and alkalinity data for Rocky Mountain National Park.

Sample ID	Elev[a]	F pH[b]	Temp[c]	Cond[d]	L pH[e]	Alk[f]
			Roaring River			
GA01I	3511.30	6.23	2.0	12.7	6.45	26.0
GA02S	3499.10	6.95	8.0	19.2	6.98	96.0
GA04L	3511.30	6.63	13.0	9.6	6.81	47.0
GA05O	3511.30	6.50	11.0	10.2	6.66	50.0
GA08O	3511.30	6.50	11.5	10.6	6.66	44.0
GA10I	3364.99	7.05	11.0	19.2	7.09	98.0
GA12L	3352.80	6.03	14.0	15.8	6.70	81.0
GA16O	3352.80	6.19	14.0	14.3	6.89	83.0
GA18S	3291.84	6.08	14.0	10.0	6.98	83.0
GA20S	3194.30	6.65	13.0	17.1	6.96	78.0
GA24S	3169.92	6.47	13.0	16.0	6.78	75.0
GA26S	3017.52	6.30	13.5	15.1	6.96	95.0
GA28S	2901.70	6.40	13.0	13.5	6.87	77.0
GA30S	2804.16	6.09	13.0	13.2	7.01	72.0
GA32S	2621.28	6.14	8.0	15.4	6.97	92.0
GA32SR	2621.28	6.14	8.0	15.4	6.87	97.0
GA46S	2926.08	6.00	14.0	12.3	6.83	57.0
			Ypsilon Creek			
GB02I	3413.76	5.90	5.0	--	6.43	31.0
GB06O	3413.76	5.63	8.0	21.3	6.56	31.0
GB08I	3352.80	5.96	9.0	20.9	6.56	35.0
GB09I	3352.80	6.20	6.0	--	6.78	66.0
GB10L	3352.80	6.05	13.0	19.9	6.65	42.0
GB12O	3352.80	5.94	11.0	19.9	6.66	42.0
GB14I	3279.65	6.27	13.0	21.9	6.68	60.0
GB16O	3279.65	6.50	11.0	21.4	6.75	54.0
GB18S	3108.96	--	--	11.8	6.69	63.0
GB19I	3462.53	6.41	11.0	16.5	6.09	16.0
GB22O	3462.53	6.41	8.0	19.1	6.05	19.0
GB26O	3462.53	6.58	12.0	20.4	6.53	26.0
GB30L	3462.53	6.83	14.0	22.2	6.58	34.0
GB32O	3462.53	6.78	13.0	19.0	6.61	38.0
GB34S	3352.80	6.12	8.0	22.7	6.56	33.0
GB35S	3352.80	6.17	8.0	20.4	6.33	28.0
GB38I	3218.69	6.45	8.0	15.9	6.65	33.0
GB40L	3218.69	7.00	13.0	15.1	6.59	42.0
GB40LR	3218.69	7.00	13.0	15.1	6.65	36.0
GB42O	3218.69	6.83	13.0	15.5	6.56	37.0

Table C-1. (continued)

Sample ID	Elev[a]	F pH[b]	Temp[c]	Cond[d]	L pH[e]	Alk[f]
Upper Fall River						
GC02S	3413.76	0.00	7.0	42.2	7.32	377.0
GC02SR	3413.76	0.00	7.0	42.2	7.61	358.0
GC03S	3413.76	0.00	6.0	26.5	7.12	172.0
GC04S	3535.68	0.00	6.0	10.0	6.88	69.0
GC06S	3523.49	6.99	5.0	15.0	7.13	138.0
GC08S	3523.49	6.89	5.0	39.6	7.47	357.0
GC10S	3511.30	6.90	5.0	24.8	7.07	216.0
GC11S	3401.57	0.00	10.0	9.6	6.65	51.0
GC12S	3401.57	0.00	10.0	22.5	7.07	184.0
GC13S	2926.08	0.00	8.0	23.6	7.38	170.0
GC14S	2816.35	0.00	9.0	14.6	7.05	119.0
GC16S	2767.58	0.00	9.0	21.9	7.21	162.0
GC18S	2657.86	6.13	7.0	22.1	7.17	167.0
GC20S	2657.86	6.23	8.0	14.3	6.42	87.0
GC24S	2657.86	6.20	8.0	20.4	6.93	146.0
Tyndall Gorge						
MA02I	3084.58	5.66	8.0	27.4	6.36	29.0
MA02IR	3084.58	5.66	8.0	27.4	6.36	24.0
MA06O	3084.58	5.61	12.0	23.4	6.56	31.0
MA08I	3023.62	5.81	11.0	27.0	6.46	39.0
MA12O	3023.62	5.77	15.0	26.6	6.77	38.0
MA16S	2804.16	--	--	12.0	6.60	62.0
Loch Vale						
MC02I	3474.72	6.66	1.5	53.3	6.46	46.0
MC04L	3474.72	6.66	9.0	30.9	6.46	28.0
MC06O	3474.72	6.48	8.0	31.3	5.98	36.0
MC12S	3267.46	6.55	9.0	34.1	6.38	27.0
MC14S	3169.92	5.92	6.0	29.5	6.43	32.0
MC14SR	3169.92	5.92	6.0	29.5	6.47	29.0
MC18I	3328.42	6.21	2.0	36.3	6.04	17.0
MC20L	3328.42	0.00	--	--	6.53	22.0
MC22O	3328.42	7.05	11.0	31.9	6.42	32.0
MC24I	3316.22	6.24	12.0	35.7	6.44	24.0
MC28O	3316.22	6.04	13.0	34.5	--	32.0
MC30I	3108.96	6.51	13.0	38.8	6.46	40.0
MC32L	3108.96	6.81	19.0	37.1	6.74	43.0
MC34O	3108.96	5.93	15.0	33.4	6.66	47.0
MC36S	2987.04	5.94	16.0	10.0	6.57	43.0

Table C-1. (continued)

Sample ID	Elev[a]	F pH[b]	Temp[c]	Cond[d]	L pH[e]	Alk[f]
			Glacier Creek			
MD02I	3535.68	6.10	8.0	28.0	5.66	10.0
MD06O	3535.68	6.15	12.0	18.5	5.89	11.0
MD08I	3230.88	6.22	11.0	26.7	--	--
MD10I	3230.88	6.21	6.0	20.8	6.09	30.0
MD14O	3230.88	6.34	11.0	24.4	6.56	52.0
MD24I	3474.72	6.17	3.0	33.7	6.52	33.0
MD26L	3474.72	6.82	12.0	26.6	6.66	38.0
MD28O	3468.62	6.49	12.0	28.2	6.66	35.0
MD32L	3413.76	6.89	14.0	29.3	6.65	43.0
MD34O	3413.76	6.90	13.0	23.9	6.52	64.0
MD38S	3145.54	6.47	14.0	25.5	6.63	53.0
MD40S	3035.81	6.44	14.0	26.5	6.52	54.0
MD42O	3035.81	6.51	16.0	25.7	6.79	47.0
MD44L	3035.81	6.48	18.0	26.5	6.66	50.0
MD46O	3035.81	6.61	15.0	26.3	6.75	45.0
MD48S	2974.85	5.97	16.0	9.9	6.73	65.0
MD50S	2865.12	5.88	12.0	10.1	6.73	65.0
MD52S	2755.39	0.00	0.0	10.1	0.00	53.0
			Upper Colorado River			
V01I	3511.30	0.00	11.0	10.5	6.91	85.0
V02S	3230.88	0.00	0.0	76.0	7.93	682.0
V03O	3499.10	0.00	0.0	30.2	7.38	280.0
V04S	3255.26	0.00	0.0	29.6	7.62	242.0
V06S	3182.11	0.00	0.0	53.0	7.61	427.0
V08S	3169.92	0.00	0.0	56.4	7.69	607.0
V10S	3108.96	0.00	0.0	46.6	7.58	375.0
V10SR	3108.96	0.00	0.0	0.0	7.61	366.0
V12S	3115.06	6.95	10.0	72.9	8.03	580.0
V14S	3121.15	6.71	9.0	64.8	7.56	374.0
V16S	3121.15	6.70	10.0	52.0	7.44	361.0
V18I	3486.91	6.82	9.0	18.7	7.29	146.0
V20L	3486.91	9.00	11.0	41.6	7.72	342.0
V22O	3486.91	6.85	110.0	41.6	7.65	341.0
V24S	3230.88	7.19	7.0	45.8	7.58	357.0
V25S	3121.15	0.00	0.0	0.0	7.69	367.0
V28S	3121.15	6.70	8.0	64.0	7.76	480.0
V28SR	3121.15	0.00	0.0	0.0	7.76	480.0
V30S	3133.34	0.00	0.0	0.0	7.33	202.0
V32S	3133.34	0.00	0.0	26.1	6.56	50.0
V34S	3133.34	0.00	0.0	0.0	0.00	0.0
V34SR	3133.34	0.00	0.0	0.0	0.00	0.0
V36S	3133.34	0.00	0.0	48.9	7.78	443.0
V38S	3108.96	6.40	9.0	22.9	7.20	189.0

Table C-1. (concluded)

Sample ID	Elev[a]	F pH[b]	Temp[c]	Cond[d]	L pH[e]	Alk[f]
			East Inlet			
MW02I	3316.22	5.78	7.0	13.0	0.00	80.0
MW060	3316.22	8.13	11.0	12.0	6.92	80.0
MW08I	3169.92	0.00	12.0	11.4	6.79	72.0
MW120	3169.92	0.00	16.0	10.9	6.84	93.0
MW15I	3145.54	0.00	8.0	8.8	7.00	94.0
MW16I	3145.54	0.00	15.0	10.2	6.80	68.0
MW200	3145.54	0.00	16.0	9.8	7.10	76.0
MW22I	3108.96	0.00	13.0	9.3	6.73	60.0
MW260	3108.96	0.00	15.5	10.0	6.84	83.0
MW30S	3084.58	0.00	0.0	11.6	6.96	77.0
MW32I	3023.62	0.00	0.0	12.6	6.85	73.0
MW360	3011.42	0.00	17.0	10.2	6.81	91.0
MW38S	2865.12	0.00	0.0	12.3	6.76	80.0
MW40S	2889.50	0.00	0.0	15.4	6.45	121.0
MW40SR	2889.50	0.00	0.0	15.4	6.86	120.0
MW42S	2865.12	0.00	0.0	14.4	6.64	94.0
MW44S	2791.97	0.00	0.0	13.4	7.10	96.0

[a] Elev = elevation in meters.
[b] F pH = field pH in SU.
[c] Temp = temperature in °C.
[d] Cond = conductivity in µmohs/cm.
[e] L pH = lab pH in SU.
[f] Alk = alkalinity in µeq/l.

Table C-2. Lake and stream chemistry data for Rocky Mountain National Park.

Sample ID	Elev[a]	Na[b]	K	Mg	Ca	NH_4	Cl	NO_3+NO_2	SO_4	PO_4	SiO_2
					Roaring River						
GA01I	3511.30	9.70	3.45	13.41	56.64	0.39	9.36	19.39	31.94	0.33	40.90
GA02S	3499.10	37.67	3.48	30.20	86.83	0.00	5.50	13.60	44.31	0.14	144.32
GA04L	3511.30	10.79	2.66	11.44	59.43	0.00	4.37	3.32	24.22	0.00	35.70
GA05O	3511.30	10.05	2.71	10.45	55.14	0.00	5.05	3.31	27.11	0.00	32.33
GA08O	3511.30	11.27	2.86	11.93	55.79	0.00	8.10	9.93	30.92	0.00	29.00
GA10I	3365.00	41.06	4.30	29.54	93.76	0.00	6.35	11.97	38.83	0.00	142.13
GA12L	3352.80	29.75	4.42	23.21	82.19	0.00	6.29	6.05	34.50	0.09	97.43
GA16O	3352.80	29.41	3.50	22.46	79.69	0.00	5.98	5.79	33.52	0.09	95.22
GA18S	3291.80	30.45	3.91	18.51	59.53	0.00	5.78	0.35	37.52	0.00	101.34
GA20S	3194.30	31.62	3.45	18.93	56.54	0.00	4.65	6.84	36.19	0.09	105.80
GA24S	3169.90	30.62	3.22	26.83	73.30	0.00	4.09	6.47	31.92	0.14	112.86
GA26S	3017.50	31.32	2.58	21.64	64.07	1.05	6.26	3.11	29.13	0.14	94.16
GA28S	2901.70	29.97	4.07	21.48	65.32	0.00	4.80	7.00	32.71	0.13	112.86
GA30S	2804.20	30.54	4.07	19.83	57.98	0.00	7.50	6.95	32.13	0.14	116.56
GA32S	2621.30	39.89	4.02	28.64	77.30	0.00	5.58	5.77	38.37	0.09	147.73
GA32SR	2621.30	40.50	4.35	29.29	78.14	0.00	5.98	5.79	37.81	0.13	145.98
GA46S	2926.10	23.97	3.94	19.01	50.85	0.00	4.60	8.76	32.71	0.17	97.96
					Ypsilon Creek						
GB02I	3413.80	17.62	5.04	11.68	38.07	1.11	3.27	18.06	27.94	0.27	66.79
GB06O	3413.80	19.97	3.58	10.78	42.61	0.00	2.28	20.21	36.31	0.27	75.42
GB08I	3352.80	19.44	2.74	11.11	45.46	0.00	2.62	16.00	35.73	0.22	75.69
GB09I	3352.80	33.84	4.17	13.08	43.46	0.00	3.64	0.26	24.86	0.00	119.86
GB10L	3352.80	24.71	4.48	14.40	52.59	0.00	4.88	14.89	37.02	0.22	94.34
GB12O	3352.80	24.23	3.94	12.51	47.95	0.00	2.48	14.45	36.10	0.14	93.50
GB14I	3279.60	32.02	4.86	16.95	53.14	0.00	2.00	12.64	40.96	0.20	116.63
GB16O	3279.60	31.45	4.60	16.54	50.85	0.00	1.35	4.98	37.92	0.00	114.05
GB18S	3109.00	29.88	4.35	16.62	53.49	0.00	2.71	9.40	38.81	0.11	113.78
GB19I	3462.50	3.52	2.12	5.60	15.12	0.00	0.14	8.53	18.01	0.20	--
GB22O	3462.50	8.92	3.45	7.24	27.15	0.00	0.20	12.11	25.92	0.14	31.47
GB26O	3462.50	8.00	2.92	9.63	33.43	1.22	4.15	11.11	21.49	0.00	26.71
GB30L	3462.50	18.40	6.55	21.31	36.13	0.33	3.81	9.74	29.50	0.00	54.40
GB32O	3462.50	17.70	5.47	18.76	34.88	0.00	4.80	2.44	30.15	0.25	46.19
GB34S	3352.80	16.66	4.12	11.52	31.54	0.00	2.26	13.82	21.26	0.27	78.95
GB35S	3352.80	16.31	3.76	12.59	30.34	0.00	2.51	13.24	24.26	0.27	64.35
GB38I	3218.70	16.18	4.40	12.59	35.58	0.00	2.82	11.61	27.17	0.19	64.95
GB40L	3218.70	14.88	3.53	11.93	34.48	0.00	3.95	7.10	20.24	0.00	50.35
GB40LR	3218.70	18.88	4.68	13.50	37.03	0.00	5.92	9.18	23.86	0.08	62.30
GB42O	3218.70	15.66	3.89	13.25	36.93	0.00	3.58	8.85	23.86	0.13	62.07

Table C-2. (continued)

Sample ID	Elev[a]	Na[b]	K	Mg	Ca	NH_4	Cl	NO_3+NO_2	SO_4	PO_4	SiO_2
					Upper Fall River						
GC02S	3413.80	31.75	9.23	162.11	198.15	0.00	5.81	3.06	87.62	0.00	137.62
GC02SR	3413.80	32.84	8.80	161.12	198.00	0.00	6.52	3.18	87.89	0.00	129.34
GC03S	3413.80	29.49	8.31	80.97	120.56	0.00	6.43	8.66	76.21	0.11	144.12
GC04S	3535.70	23.10	7.80	13.25	44.66	0.00	4.20	2.27	--	0.36	146.22
GC06S	3523.50	36.93	6.29	37.52	73.95	0.00	5.84	3.71	19.43	0.09	167.00
GC08S	3523.50	44.98	10.54	137.75	200.20	0.00	14.27	3.00	71.40	0.20	162.97
GC10S	3511.30	40.06	7.95	78.75	123.80	0.00	8.80	3.37	44.25	0.00	164.23
GC11S	3401.60	30.58	2.84	12.59	30.84	0.00	3.55	5.35	16.68	0.30	138.95
GC12S	3401.60	38.76	6.68	68.30	107.53	1.11	9.93	1.74	37.83	0.02	167.98
GC13S	2926.10	42.85	11.33	67.48	102.30	0.55	11.31	6.27	44.83	0.00	122.48
GC14S	2816.40	46.54	2.33	35.63	66.82	0.00	5.56	1.00	36.98	0.09	216.43
GC16S	2767.60	46.41	10.28	56.04	98.00	0.00	8.55	4.63	49.70	0.00	185.88
GC18S	2657.90	46.46	9.72	57.93	99.70	0.00	8.26	7.02	51.82	0.00	180.11
GC20S	2657.90	40.45	3.09	26.74	70.96	0.00	6.68	9.29	20.11	0.09	189.23
GC24S	2657.90	47.11	8.21	53.16	96.61	0.00	8.21	6.81	46.04	0.14	194.93
					Tyndall Gorge						
MA02I	3084.60	14.40	3.79	9.79	37.67	0.00	--	1.66	--	0.20	48.29
MA02IR	3084.60	14.35	3.81	9.71	38.32	0.00	2.88	6.53	30.09	0.27	46.28
MA060	3084.60	16.01	4.25	12.84	54.14	0.00	3.33	19.56	32.92	0.08	51.36
MA08I	3023.60	15.36	3.56	12.67	55.79	0.00	3.41	12.56	35.19	0.08	52.95
MA120	3023.60	16.44	3.48	13.41	57.63	0.00	3.75	11.19	31.65	0.09	54.56
MA16S	2804.20	18.27	3.20	17.12	62.43	0.00	3.92	12.48	31.65	0.08	70.31
					Loch Vale						
MC02I	3474.70	27.97	7.65	33.08	138.72	0.67	12.72	57.90	109.02	1.19	119.11
MC04L	3474.70	7.22	1.74	6.42	22.36	0.00	1.97	--	--	0.20	33.78
MC060	3474.70	7.39	1.89	6.42	22.06	0.00	1.07	4.98	--	0.20	30.10
MC12S	3267.50	12.18	2.12	7.24	29.09	0.00	0.59	10.42	16.70	0.20	51.29
MC14S	3169.90	12.48	2.10	10.45	36.93	0.39	4.06	14.37	21.45	0.14	45.74
MC14SR	3169.90	12.48	2.02	9.71	39.72	0.00	1.30	14.74	26.71	0.19	57.19
MC18I	3328.40	10.16	1.74	10.20	36.08	0.33	3.33	17.81	18.51	0.25	26.99
MC20L	3328.40	12.09	2.10	9.13	39.22	0.00	3.13	10.35	30.27	0.19	34.26
MC220	3328.40	9.87	1.79	11.19	37.43	1.55	4.48	11.53	23.19	0.22	28.85
MC24I	3316.20	9.92	1.71	11.36	37.77	1.44	4.37	12.93	24.90	0.20	30.84
MC280	3316.20	10.18	1.97	11.44	40.47	0.61	4.23	11.52	25.96	0.22	30.81
MC30I	3109.00	11.70	2.02	12.18	42.42	0.67	1.06	11.27	24.88	0.20	35.56
MC32L	3109.00	19.36	3.17	13.91	44.71	1.55	9.31	10.69	27.59	0.31	36.33
MC340	3109.00	14.70	2.35	14.32	46.66	1.16	5.02	10.45	27.69	0.14	35.64
MC36S	2987.00	13.14	2.05	14.32	44.91	0.67	5.64	11.02	28.25	0.17	36.04

Table C-2. (continued)

Sample ID	Elev[a]	Na[b]	K	Mg	Ca	NH_4	Cl	NO_3+NO_2	SO_4	PO_4	SiO_2
					Glacier Creek						
MD02I	3535.70	4.00	2.12	3.37	18.81	1.33	2.09	13.72	2.31	0.42	--
MD060	3535.70	5.48	1.25	5.10	23.80	1.61	3.50	11.53	14.49	0.09	15.23
MD08I	3230.90	9.96	1.07	7.57	41.97	0.00	3.75	0.18	18.86	0.00	36.04
MD10I	3230.90	10.66	2.56	6.50	38.42	0.00	1.41	14.43	15.66	0.34	40.76
MD140	3230.90	14.27	2.79	8.64	47.41	0.00	2.31	9.95	20.36	0.00	46.06
MD24I	3474.70	15.70	3.91	9.96	47.06	0.00	2.79	22.39	15.57	0.31	54.11
MD26L	3474.70	18.01	3.81	10.04	48.50	0.00	3.92	13.81	17.03	0.19	56.27
MD280	3468.60	17.27	3.71	10.20	45.86	1.05	3.55	13.19	16.03	0.27	55.75
MD32L	3413.80	17.97	3.71	10.53	51.60	0.00	3.41	12.32	18.47	0.23	40.75
MD340	3413.80	17.44	3.27	10.53	47.41	0.00	3.50	11.98	16.01	0.16	57.71
MD38S	3145.50	16.53	3.02	10.62	53.59	0.00	3.41	8.13	13.91	0.11	52.66
MD40S	3035.80	18.40	2.92	11.77	53.54	0.00	3.41	7.64	14.93	0.08	54.56
MD420	3035.80	18.31	3.17	11.60	50.45	0.00	6.46	7.63	13.33	0.09	53.25
MD44L	3035.80	17.40	2.79	11.85	51.55	0.00	4.01	6.42	11.66	0.00	52.22
MD460	3035.80	17.88	2.07	11.27	51.75	0.00	4.43	6.50	24.53	0.00	42.62
MD48S	2974.80	16.18	3.38	12.67	51.90	0.00	4.03	8.81	13.26	0.17	48.77
MD50S	2865.10	16.62	3.48	13.08	54.04	0.00	4.91	8.32	14.85	0.09	47.99
MD52S	2755.40	19.84	4.32	14.07	57.14	0.00	1.69	17.72	10.39	0.31	60.38
					Upper Colorado River						
V01I	3511.30	7.61	1.15	7.98	77.00	0.00	4.68	2.13	20.47	0.23	9.82
V02S	3230.90	121.10	4.91	165.49	17.66	0.00	9.76	1.63	133.30	0.11	182.16
V030	3499.10	15.05	1.18	68.30	197.85	0.72	0.08	8.32	28.63	0.17	30.88
V04S	3255.30	88.48	13.71	43.53	118.96	0.00	7.42	7.03	48.22	0.27	430.91
V06S	3182.10	--	8.57	132.73	257.14	0.00	7.33	3.60	101.88	0.13	203.95
V08S	3169.90	38.15	7.88	--	404.09	0.00	10.44	4.81	153.12	0.13	118.62
V10S	3109.00	--	10.49	98.66	215.12	0.00	10.24	1.71	86.60	0.08	276.39
V10SR	3109.00	78.47	10.38	97.51	215.82	0.00	10.52	1.52	86.01	0.09	274.00
V12S	3115.10	37.15	6.60	0.00	370.76	0.00	10.01	1.44	154.24	0.13	124.85
V14S	3121.20	26.84	7.26	117.10	381.84	0.00	7.93	7.92	159.93	0.00	105.68
V16S	3121.20	37.28	7.72	85.99	337.62	1.72	7.64	2.40	144.94	0.00	107.90
V18I	3486.90	3.91	3.50	33.57	116.87	0.00	7.36	9.45	--	0.27	17.18
V20L	3486.90	11.92	7.24	60.89	311.38	1.16	4.40	2.73	55.11	0.34	51.24
V220	3486.90	13.62	7.90	63.44	277.25	0.00	6.15	9.06	58.15	0.33	59.73
V24S	3230.90	19.71	7.57	83.69	290.77	0.00	8.83	16.92	78.79	0.17	65.89
V25S	3121.20	35.76	7.29	100.47	262.72	0.00	15.09	0.92	79.91	0.14	74.69
V28S	3121.20	36.76	6.78	126.72	436.63	1.33	27.13	11.34	113.89	0.00	59.13
V28SR	3121.20	21.45	8.82	101.71	364.77	0.00	7.98	17.13	107.96	0.00	70.62
V30S	3133.30	27.88	5.09	47.81	191.47	0.00	5.84	3.29	93.55	0.00	107.98
V32S	3133.30	39.15	5.27	26.17	119.41	0.00	2.20	12.37	119.81	0.00	174.36
V38S	3109.00	62.64	9.21	25.43	101.60	0.00	2.82	0.79	44.43	0.00	33.78

Table C-2. (concluded)

Sample ID	Elev[a]	Na[b]	K	Mg	Ca	NH_4	Cl	NO_3+NO_2	SO_4	PO_4	SiO_2
					East Inlet						
MW02I	3316.20	16.83	2.25	16.79	119.56	0.00	5.61	30.98	61.19	0.19	72.54
MW060	3316.20	15.36	2.53	14.98	104.74	0.00	10.55	7.21	52.57	0.45	58.65
MW08I	3169.90	20.62	3.48	15.55	96.86	0.00	5.25	9.03	50.35	0.14	71.69
MW120	3169.90	20.84	1.38	14.98	71.61	1.22	4.88	2.92	22.82	0.14	55.12
MW15I	3145.50	37.06	2.20	15.63	75.40	0.33	4.23	1.73	26.94	0.11	172.01
MW16I	3145.50	27.58	2.33	13.74	73.30	0.33	4.94	1.15	36.44	0.08	95.19
MW200	3145.50	25.40	1.61	12.18	66.32	0.44	3.92	0.55	35.67	0.00	80.42
MW22I	3109.00	26.06	1.64	12.51	65.92	0.00	4.20	--	35.96	0.08	84.92
MW260	3109.00	22.36	1.94	13.99	68.56	0.28	4.99	1.16	28.73	0.08	71.41
MW30S	3084.60	23.32	1.94	12.59	63.67	0.00	4.20	1.61	29.09	0.09	69.79
MW32I	3023.60	24.27	2.25	13.91	68.41	0.00	4.01	2.50	28.67	0.08	68.99
MW360	3011.40	23.19	2.56	14.48	70.36	0.00	4.46	1.35	27.82	0.09	64.92
MW38S	2865.10	24.23	2.33	15.22	70.96	0.00	3.67	2.08	27.80	0.00	68.50
MW40S	2889.50	30.97	2.89	22.55	90.47	0.00	3.53	3.89	32.40	0.00	100.57
MW40SR	2889.50	32.45	3.22	23.04	92.22	0.00	3.55	3.89	35.67	0.00	101.45
MW42S	2865.10	42.02	2.97	16.05	58.58	0.00	3.19	0.45	35.25	0.00	211.87
MW44S	2792.00	28.19	2.48	17.03	75.80	0.00	2.93	2.66	28.82	0.00	93.57

[a] Elev in meters.
[b] All ions in µeq/l; SiO_2 in µM/l.
-- = missing values.

APPENDIX D

WATER CHEMISTRY DATA, YELLOWSTONE NATIONAL PARK

Table D-1. Recent lake chemistry data for Yellowstone National Park Lakes.

	Lake	Alk	Year	Elev	pH	Ca	Mg	Na	K	SO_4	Cl	Sum of cations	Ion balance
001	Turbid	0	1977	2389	4.20	419.2	361.9	522.0	74.7	3185.5	138.2	1377.8	-82.8
002	Beaver L	40	1976	2249	5.10	698.6	279.7	3654.0	95.6	2290.2	2482.5	4727.9	-1.8
003	Buffalo	40	1976	2347	6.90	39.9	8.2	26.1	5.9	41.6	28.2	80.1	-31.3
004	Wrangler	40	1977	2396	7.20	39.9	8.2	30.5	7.9	20.8	25.4	86.5	0.3
005	Summit	60	1977	2607	6.30	39.9	16.5	30.5	9.2	20.8	36.7	96.1	-20.0
006	Dewdrop	80	1979	2481	6.50	79.8	123.4	60.9	12.8	124.9	36.7	276.9	13.6
007	Dryad	80	1977	2529	6.70	59.9	16.5	39.2	13.3	20.8	39.5	128.9	-8.5
008	Mary	80	1977	2519	7.00	99.8	16.5	60.9	34.0	20.8	42.3	211.2	38.4
009	Obsidian	80	1980	2365	6.50	119.8	32.9	34.8	15.3	114.5	42.3	202.8	-15.5
010	Shelf	80	1979	2793	6.50	79.8	41.1	26.1	10.2	41.6	14.1	157.2	14.7
011	Mirror	100	1975	2705	6.80	39.9	16.5	52.2	12.3	20.8	28.2	120.9	-20.8
012	Robinson	100	1976	1981	5.90	79.8	41.1	17.4	5.6	20.8	28.2	143.9	-3.5
013	Scaup	104	1980	2420	6.75	109.8	32.9	60.9	20.5	52.1	42.3	224.1	12.2
014	High	120	1979	2675	7.00	159.7	41.1	78.3	51.1	124.9	22.6	330.2	21.0
015	Wyodaho	120	1976	2071	6.75	79.8	41.1	47.9	12.5	41.6	28.2	181.3	-4.6
016	Sedge	130	1970	2484	7.10	68.9	19.7	30.0	24.0	73.3	4.2	142.6	-44.2
017	Beach	146	1970	2484	6.90								
018	Crag	160	1979	2683	6.80	79.8	41.1	30.5	15.3	41.6	19.8	166.7	-28.2
019	Crescent	160	1979	2622	7.20	119.8	57.6	39.2	23.0	145.7	31.0	239.6	-33.7
020	Mt. Everts A	160	1976	2211	6.90	159.7	41.1	21.8	4.6	62.5	0.0	227.2	2.1
021	Ranger	160	1976	2128	7.00	99.8	57.6	34.8	11.0	41.6	28.2	203.2	-12.3
022	Sheridan	160	1978	2249	8.75	79.8	123.4	213.2	20.5	229.0	141.1	436.9	-19.3
023	Forest	192	1980	2262	7.00	174.7	24.7	60.9	10.2	43.7	42.3	270.5	-2.7
024	Cygnet A	200	1978	2530	6.90	79.8	41.1	174.0	15.3	20.8	39.5	310.2	17.5
025	Ice	200	1980	2402	7.10	134.7	32.9	78.3	30.7	50.0	25.4	276.6	0.4
026	Mallard	200	1973	2447	6.80								
027	Trilobite B	200	1978	2676	7.80	548.9	181.0	26.1	5.1	41.6	28.2	761.1	95.3
028	Delacy E	220	1972	2596	6.50								
029	Delacy W	220	1972	2596	6.60								
030	Harlequin	220	1979	2100	5.30	379.2	123.4	365.4	89.5	374.8	2.5	957.5	46.3
031	Cascade	240	1978	2432	7.20	159.7	41.1	156.6	12.8	135.3	53.6	370.2	-14.7
032	Cygnet B	240	1978	2530	6.60	49.9	131.6	230.6	12.8	20.8	48.0	424.9	31.6
033	Cygnet C	240	1978	2530	6.60	119.8	41.1	200.1	23.0	41.6	33.9	384.0	19.6
034	Cygnet E	240	1978	2530	6.75	119.8	41.1	178.4	23.0	41.6	39.5	362.3	12.1
035	Duck	240	1979	2374	6.80	254.5	82.3	91.4	33.2	20.8	28.2	461.4	45.9
036	Lake of the Woods	240	1974	2348	6.00	159.7	0.0	74.0	40.9	187.4	0.0	274.6	-43.5
037	Virginia	240	1974	2499	6.80	119.8	0.0	95.7	23.0	41.6	0.0	238.5	-16.6
038	Wapiti	240	1975	2573	7.25	119.8	57.6	104.4	33.8	20.8	28.2	315.6	8.8
039	Glade	246	1979	2952	7.00	119.8	57.6	78.3	17.9	208.2	28.2	273.6	-55.2
040	Unnamed B	280	1976	1981	6.85	159.7	41.1	108.8	28.9	41.6	28.2	338.5	-3.3
041	Lilypad	320	1976	1957	7.10	199.6	123.4	82.7	14.1	20.8	28.2	419.8	12.9
042	Phoneline	320	1976	1945	6.40	279.4	197.4	104.4	7.7	124.9	28.2	588.9	21.8
043	Unnamed A	320	1976	1981	7.10	159.7	82.3	204.5	16.9	104.1	28.2	463.4	2.4
044	Winegar	320	1976	1969	7.10	199.6	82.3	82.7	8.7	41.6	28.2	373.3	-4.3
045	Delusion	340	1971	2385	7.20								

Table D-1. (continued)

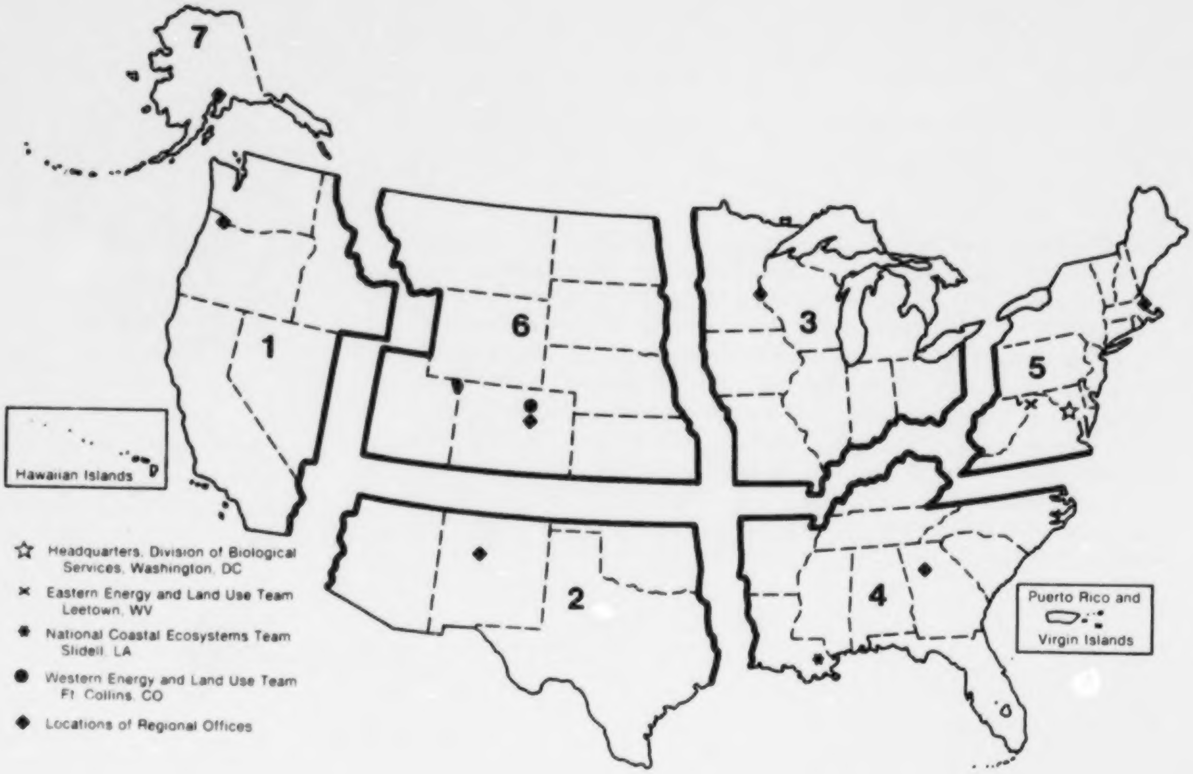
	Lake	Alk	Year	Elev	pH	Ca	Mg	Na	K	SO_4	Cl	Sum of cations	Ion balance
046	Fern	360	1975	2513	5.60	299.4	57.6	870.0	155.0	624.6	338.5	1382.0	4.4
047	Pocket	360	1972	2470	6.80								
048	Wolf	360	1979	2438	7.40	239.5	41.1	169.7	48.6	124.9	28.2	498.9	-2.8
049	Cygnet D	380	1979	2530	6.60	259.5	139.8	204.5	26.8	232.0	33.9	630.6	-2.4
050	Hering	400	1973	2250	7.10								
051	Trilobite C	400	1978	2713	8.30	279.4	41.1	8.7	5.1	41.6	31.0	334.3	-34.3
052	Ribbon	440	1972	2384	7.00								
053	Grebe	480	1979	2448	7.20	239.5	156.3	208.8	51.1	177.0	28.2	655.7	-4.4
054	Tanager	500	1973	2125	8.00								
055	YS W Thumb	524	1980	2357	7.40	319.4	82.3	408.9	51.1	374.8	172.1	861.7	-21.6
056	Riddle	540	1979	2413	6.80	239.5	238.6	130.5	0.0	20.8	28.8	608.6	3.3
057	YS SE Arm	557	1980	2357	7.40	279.4	123.4	356.7	46.0	208.2	143.9	805.5	-12.1
058	YS S Arm	557	1980	2357	7.80	259.5	181.0	400.2	51.1	208.2	158.0	891.8	-3.5
059	Shoshone	574	1980	2375	7.30	249.5	98.7	826.5	61.4	84.3	297.6	1236.1	25.6
060	YS Steve Island	574	1980	2357	7.40	279.4	197.4	391.5	48.6	229.0	172.1	916.9	-6.2
061	Sylvan	600	1978	2563	7.60	319.4	82.3	95.7	7.7	83.3	31.0	505.1	-34.3
062	Lewis	639	1980	2372	7.40	188.0	87.7	695.7	86.1	125.6	217.2	1057.5	7.4
063	Panther Creek	640	1979	2591	6.50	479.0	156.3	30.5	7.7	41.6	19.8	673.5	-4.1
064	Heart	716	1980	2271	7.60	294.4	151.0	1609.7	83.5	333.0	912.0	2138.6	8.7
065	Alder	720	1976	2363	8.20	399.2	320.8	130.5	41.4	124.9	28.2	891.9	2.1
066	Goose	760	1979	2198	8.00	239.5	296.1	696.0	74.2	87.4	56.4	1305.8	36.4
067	Mt. Everts B	760	1976	2217	8.10	439.1	320.8	78.3	56.8	20.8	28.2	895.0	10.1
068	Beula	800	1973	2249	7.20								
069	Gooseneck	840	1979	2241	7.20	469.1	41.1	609.0	61.4	104.1	28.2	1180.6	19.4
070	Pass	840	1974	2793	9.00	598.8	238.6	56.6	23.5	104.1	0.0	917.5	-2.9
071	Trilobite A	880	1978	2650	7.80	479.0	156.3	174.0	40.9	41.6	135.4	850.2	-21.7
072	Upper Gooseneck	900	1979	2240	7.80	344.3	41.1	565.5	63.9	41.6	28.2	1014.8	4.5
073	Lost	960	1980	2034	6.50	598.8	238.6	274.1	18.4	333.1	0.0	1129.9	-13.5
074	Sportsman	1040	1974	2357	8.50	848.3	238.6	134.9	47.1	41.6	0.0	1268.9	15.9
075	Grizzly	1080	1979	2289	7.80	698.6	361.9	522.0	25.6	249.9	28.2	1608.1	16.9
076	Rainbow M	1340	1974	1793	9.00	598.8	238.6	1131.0	33.8	333.1	0.0	2002.2	17.9
077	Divide	1400	1970	2207	9.20	930.1	389.9	30.0	19.9	63.5	4.2	1369.9	-6.9
078	Gallatin	1440	1979	2693	8.40	548.9	904.9	30.5	7.7	104.1	28.2	1492.0	-5.2
079	Outlet	1480	1978	2362	9.40	499.0	436.0	413.3	7.7	62.5	42.3	1356.0	-15.6
080	Basin Creek	1580	1979	2253	8.10	1297.4	378.4	169.7	17.9	416.4	28.2	1863.4	-8.1
081	McBride	1600	1975	1999	9.20	1247.5	238.6	104.4	44.5	20.8	28.2	1635.0	-0.9
082	Squaw	1680	1979	2372	7.40	598.8	361.9	8917.5	227.6	541.3	7898.8	10106.0	-0.1

Table D-1. (concluded)

	Lake	Alk	Year	Elev	pH	Ca	Mg	Na	K	SO_4	Cl	Sum of cations	Ion balance
083	Trail	1700	1971	2362	8.50	High alkalinity lakes. Only partial data set presented.							
084	Unnamed C	1800	1973	2120	7.60								
085	Ice Reservoir	1840	1974	1671	9.00								
086	Lake Beaver P	1860	1975	1987	7.25								
087	Swan	2000	1975	2215	8.20								
088	Cache	2040	1974	2454	8.00								
089	White N	2040	1975	2505	7.80								
090	B Beaver P	2160	1975	1932	8.00								
091	Lake Slide	2280	1975	1729	7.20								
092	Trout	2280	1975	2104	9.00								
093	Mammoth	2360	1975	2018	7.40								
094	Blacktail	2400	1966	2012	8.40								
095	Buck	2400	1965	2119	9.00								
096	Joffe	2400	1973	1982	8.40								
097	Tern E	2560	1975	2502	9.00								
098	B Slide	2760	1974	1729	7.50								
099	Shrimp	2800	1965	2159	8.90								
100	Fawn	2880	1975	2368	7.80								
101	White S	2880	1975	2505	7.75								
102	B Feather	3100	1966	2168	8.70								
103	Tern W	3120	1975	2504	7.70								
104	Foster	3520	1977	2018	9.00								
105	Crevice	4800	1976	1695	8.00								
106	B Trumpeter	5200	1977	1873	8.80								
107	Floating Island	8600	1966	1997	9.45								
108	L Trumpeter	10380	1977	1862	9.50								
109	Geode	21860	1979	1823	10.00								

Table D-2. Chemistry data for Yellowstone National Park lakes 1970 and earlier.

Lake	Year	Alk	Ca	Mg	Na	K	SO_4	Cl	Ion balance
Cascade	1969	340	299.9	50.2	180.1	19.9	129.9	--	--
Crag	1970	100	39.9	9.9	10.0	21.0	60.6	7.1	-69.9
Crescent	1970	270	150.2	29.6	20.0	27.1	64.5	11.2	-41.6
Grebe	1963	440	159.7	79.8	159.6	68.3	50.0	14.1	-7.5
High	1970	280	289.9	29.6	60.0	45.0	65.2	7.1	18.6
Ice	1969	110	99.8	50.2	150.1	10.0	170.1	--	--
Wolf	1969	270	250.0	50.2	180.1	29.9	170.1	31.0	7.9


7
1
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Hawaiian Islands
Puerto Rico and Virgin Islands
☆ Headquarters, Division of Biological Services, Washington, DC
× Eastern Energy and Land Use Team Leetown, WV
* National Coastal Ecosystems Team Slidell, LA
● Western Energy and Land Use Team Ft. Collins, CO
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